ELECTROACOUSTIC PROPERTIES OF MYLAR DIELECTRIC UNDERWATER SOUND TRANSDUCERS

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ELECTROACOUSTIC PROPERTIES OF MYLAR DIELECTRIC

UNDERWATER SOUND TRANSDUCERS

by

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ABSTRACT

The operation of the electrostatic transducer with mylar dielectric as a transmitter and receiver of underwater sound is studied theoretically and experimentally. Transfer functions based on equivalent circuits which enable transmitter and receiver sensitivities to be determined by a computer program are formulated. The values of the transducer parameters are theoretically postulated and then experimentally verified. The transfer functions are experimentally verified by source level measurements and reciprocity calibrations. It is shown that a transmitter-receiver combination acts as a frequency independent input-output device over a wide bandwidth.

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LIST OF SYMBOLS

C_o = blocked diaphragm electrical capacitance (F)

ϵ_o = dielectric constant of air

ϵ_m = dielectric constant of mylar

i = transducer electrical current (A)

R = output resistance of signal source (Ω)

V_o = external polarizing voltage (V)

v = signal voltage across transducer (V)

Z_E = blocked-diaphragm electrical impedance (Ω)

Z_m = open-circuit mechanical impedance (kg/sec)

Z_r = acoustic radiation impedance (kg/sec)

s = transducer mechanical stiffness (N/m)

r = transducer mechanical resistance (kg/sec)

m = diaphragm mass (kg)

f = mechanical force (N)

d = effective depth of air cushion behind diaphragm (m)

ℓ = thickness of mylar film (m)

$x_o = d + \ell$ = displacement of film with bias applied (m)

x = incremental displacement of film (m)

$u = dx/dt$ = velocity of film (m/sec)

a = transducer radius (m)

A = transducer area (m^2)

c = speed of sound in the medium (m/sec)

ρ = density of medium (kg/m^3)

ω = frequency (rad/sec)

1. Introduction

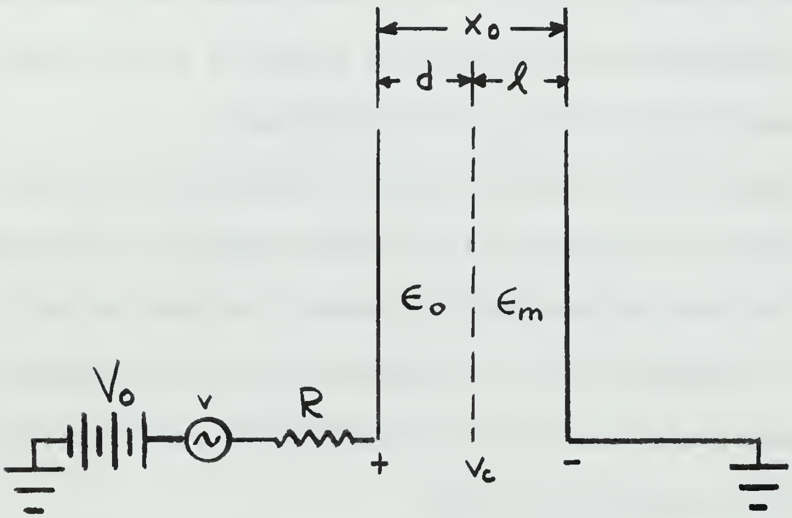
The condenser microphone has been well known for its stability and flat frequency response since its development by Wente in 1917 [1]. Its major disadvantage has been a very low capacitance resulting in a low sensitivity so that at least one stage of amplification located in close physical proximity to the microphone has been required. This low capacitance has been due primarily to the wide separation between the electrode and the diaphragm.

In recent years this drawback has been overcome by utilizing a thin, metallized, non-conducting film placed against a solid metal backplate with the bias voltage applied between the metal side of the foil and the backplate [3]. The application of the condenser microphone to waterborne sound and an investigation of its acoustic performance has been reported [5,6,14].

This report describes methods for determining the various parameters which affect the performance of the transducer as both a transmitter and a receiver, and then utilizing these parameters in theoretically determined transfer functions to predict frequency response characteristics of the transducer in both modes of operation.

2. Theory of operation

The electrostatic transducer is basically a capacitor in which one of the plates is free to move transversely as a result of changes in the applied electrical or mechanical forces. Figure 1 shows a schematic representation of the transducer with both the ac and dc



Schematic Diagram of Transducer

Figure 1

voltages applied, where v_c is the total effective voltage between the plates of the transducer. The expression for the force of attraction between the oppositely charged plates of the transducer is given by

$$f_e = -\frac{q^2}{2\epsilon A} \tag{2-1}$$

where q is the total charge on the plates of the capacitor and ϵ is the effective dielectric constant for the region between the plates. For the two-layered region of the transducer, the effective dielectric constant is given by

$$\epsilon = \frac{x_0 \epsilon_0 \epsilon_m}{\epsilon_m d + \epsilon_0 \ell} .$$

The mechanical forces which result from the motion of the film must include the effects of the mass of the diaphragm, any damping or friction involved, and the compliance or stiffness of the diaphragm. These quantities, in addition to the mechanical force of electrical origin f_e, can be related by

$$f = m\ddot{x} + r\dot{x} + sx + \frac{q^2}{2\epsilon A} \tag{2-2}$$

where x is the displacement of the film.

In considering the electrical forces involved, the basic relationships involving capacitance, charge, and voltage are given by

$$C = \frac{\epsilon A}{x} \quad \text{and} \quad V_c = \frac{q}{C} .$$

Then, the voltage equation based on Fig. 1 can be written as

$$V_0 + v = R\dot{q} + V_c$$

$$V_0 + v = R\dot{q} + q\left(\frac{x}{\epsilon A}\right) \tag{2-3}$$

The presence of the q^2 term in 2-2 and the qx term in 2-3 identify these differential equations as non-linear. If it is assumed that each variable can be expressed as an equilibrium (dc) value plus a much smaller incremental value:

$$x = x_0 + x_1 \qquad x_1 << x_0$$

$$C = C_0 + C_1 \qquad C_1 << C_0$$

$$q = q_0 + q_1 \qquad q_1 << q_0$$

then substitution of these expressions into 2-2 and 2-3 yields

$$f_0 + f_1 = m(\ddot{x}_0 + \ddot{x}_1) + r(\dot{x}_0 + \dot{x}_1) + s(x_0 + x_1) + \frac{(q_0 + q_1)^2}{2\epsilon A}$$

and

$$V_0 + v = R(\dot{q}_0 + \dot{q}_1) + (q_0 + q_1)\frac{(x_0 + x_1)}{\epsilon A} .$$

Since it has been assumed that the incremental values are much smaller than the equilibrium values, products of the incremental values can be neglected and the above equations then become

$$f_1 = m\ddot{x}_1 + r\dot{x}_1 + sx_1 + \frac{q_0 q_1}{\epsilon A} \tag{2-4}$$

and

$$v = R\dot{q}_1 + \frac{q_0 x_1}{\epsilon A} + \frac{q_1 x_0}{\epsilon A} . \tag{2-5}$$

Under steady state conditions with time variation $e^{j\omega t}$, Eqs. 2-4 and 2-5 can be expressed as

$$f_1 = j\omega m u_1 + r u_1 + \frac{s u_1}{j\omega} + \frac{q_0 \dot{i}_1}{j\omega \epsilon A} \tag{2-6}$$

and

$$v = R\dot{i}_1 + \frac{x_0 \dot{i}_1}{j\omega \epsilon A} + \frac{q_0 u_1}{j\omega \epsilon A} \tag{2-7}$$

where $\dot{i}_1 = j\omega q_1$ and $u_1 = j\omega x_1$. As a notational convenience, the subscript "1" will now be omitted so that the symbols f, x, etc., will represent their incremental values.

Now define

$$Z_m \equiv r + j\left(\omega m - \frac{s}{\omega}\right) , \tag{2-7a}$$

$$Z_E \equiv R + \frac{1}{j\omega C_0} ,$$

and

$$C_0 \equiv \frac{\epsilon A}{x_0} .$$

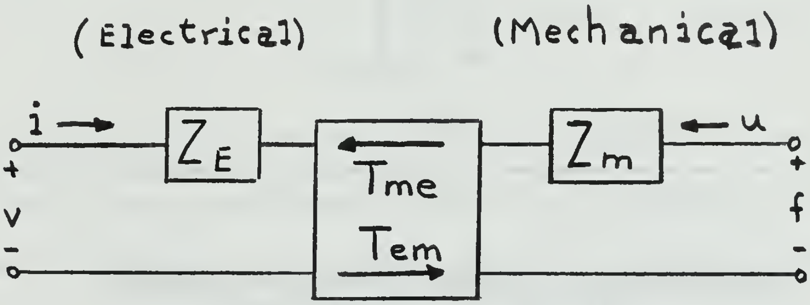
With these definitions, the expressions for force and voltage may be written in their final forms,

$$f = \frac{q_0}{j\omega \epsilon A}\dot{i} + Z_m u \tag{2-8}$$

and

$$v = Z_E i + \frac{q_0}{j\omega\epsilon A} u \; . \tag{2-9}$$

With the previous development as a basis, the transduction mechanism itself will now be investigated. The two-port network of Fig. 2 describes the transducer in which v and i, the input voltage and resultant current respectively, produce a diaphragm motion of velocity u and force f [4].



Representation of Electromechanical Transduction

Figure 2

This network can be described by the canonic equations

$$f = T_{em} i + Z_m u \tag{2-10}$$

and

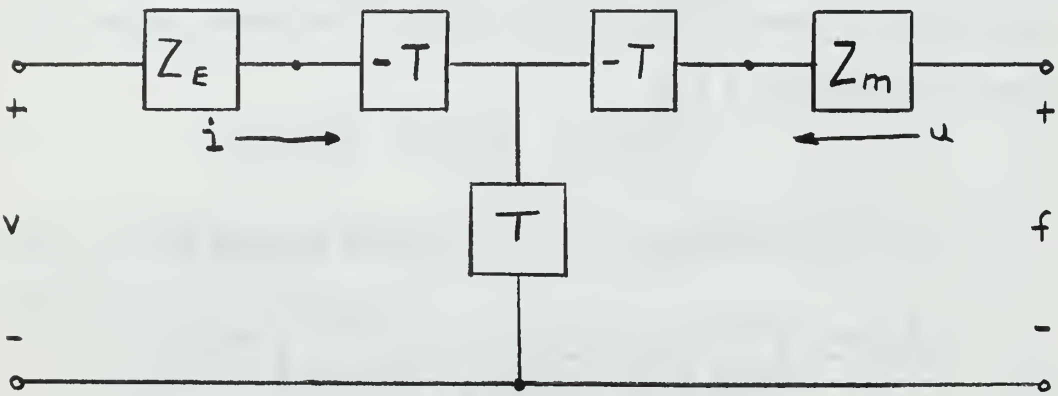
$$v = Z_E i + T_{me} u \; . \tag{2-11}$$

The transduction coefficients T_{em} and T_{me} describe the electromechanical coupling that takes place in the transducer. They are defined respectively as (1) the force acting in the mechanical side per unit current in the electrical side, and (2) the emf appearing in the electrical side per unit velocity in the mechanical side.

If 2-10 is compared with 2-9 and 2-11 with 2-8, it can be seen that

$$T_{em} = T_{me} = \frac{q_0}{j\omega\epsilon A} \equiv T \quad . \tag{2-12}$$

Thus, the electrostatic transducer obeys the reciprocity principle enabling 2-10 and 2-11 to be represented by the symmetrical two-port network of Fig. 3 [4].



Electromechanical Transduction with Symmetric
Transduction Coefficients

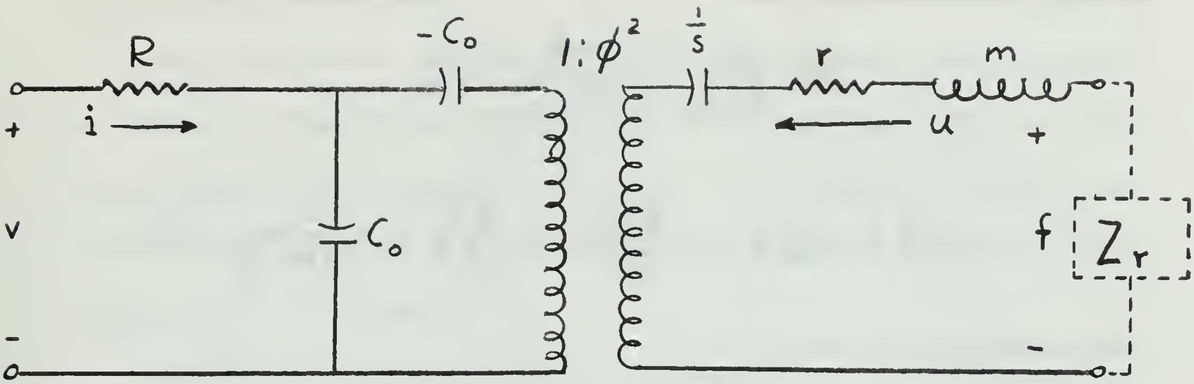
Figure 3

This figure can now be redrawn through the use of linear network theory [8] into various forms containing an ideal transformer of appropriate impedance transformation ratio. The $j\omega$ which appears in the denominator of 2-12 enables T, the transduction coefficient, to be defined as the reactance of a capacitor,

$$T \equiv \frac{1}{j\omega C_{em}} \quad \text{where} \quad C_{em} \equiv \frac{\epsilon A}{q_0} = \frac{x_0}{V_0} \quad .$$

This permits redrawing Fig. 3 in the form shown in Fig. 4 in which the turns ratio ϕ is defined as

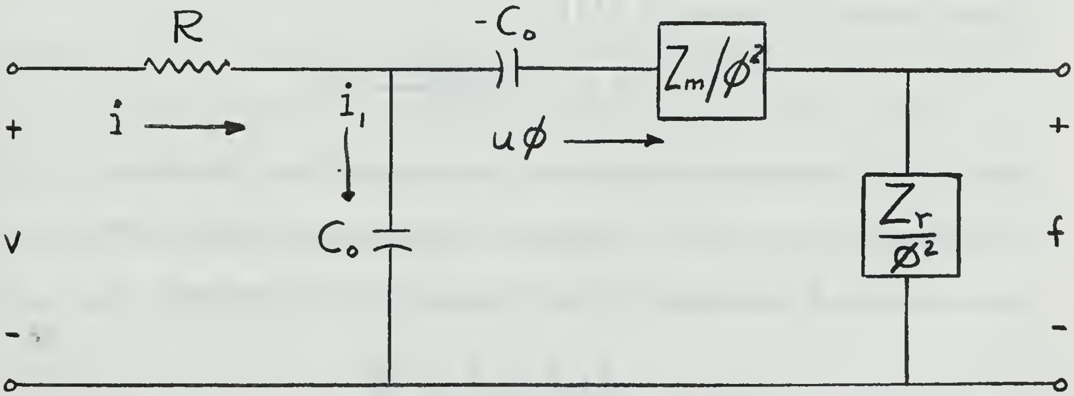
$$\phi \equiv \frac{T}{\frac{1}{j\omega C_0}} = \frac{C_0}{C_{em}} = \frac{C_0 V_0}{x_0} \quad . \tag{2-13}$$



Equivalent Electric Circuit for an Electrostatic Transducer

Figure 4

To determine the transmitter transfer function, it is convenient to remove the transformer in Fig. 4 by transferring all the mechanical quantities across it and using the parameter values reflected over to the primary side. Figure 5 represents the two-port network which results.



Equivalent Electric Circuit of an Electrostatic
Transducer in the Transmitting Mode

Figure 5

Writing two mesh equations

$$v - \dot{i}R - \frac{\dot{i}_1}{j\omega C_0} + \frac{u\phi}{j\omega C_0} = 0$$

$$u\phi\left[-\frac{1}{j\omega C_0} + \frac{Z_m}{\phi^2} + \frac{Z_r}{\phi^2}\right] - \frac{\dot{i}_1}{j\omega C_0} = 0$$

and relating the currents by

$$\dot{i} = \dot{i}_1 + u\phi$$

enables the velocity of the diaphragm to be expressed as

$$u = \frac{j\omega C_0 v\phi}{-\omega^2 R C_0^2 (Z_m + Z_r) - \phi^2 + j\omega C_0 (Z_m + Z_r)} \quad . \qquad (2\text{-}14)$$

It is convenient to express the output of an underwater transducer in terms of source level. Source level is defined as the extrapolation of the far field axial sound pressure level back to an axial distance of one meter from the effective sound source. The axial pressure amplitude produced at a distance of one meter by a piston source is given by [11]

$$P = \frac{\rho c \pi a^2 k}{2\pi} U_0$$

where U_0 is the magnitude of the velocity of the diaphragm. Substituting 2-14 into this expression enables the source level in newtons/meter^2 per volt of input signal to be expressed as

$$P = \frac{j\omega^2 a^2 \rho C_0 \phi}{2\left[-\omega^2 R C_0^2 (Z_m + Z_r) - \phi^2 + j\omega C_0 (Z_m + Z_r)\right]} \quad . \qquad (2\text{-}15)$$

The symbol Z_r has been used to denote the load across which the motion of the transducer develops the pressure. The behavior of this radiation impedance as it is affected by changes in frequency will now be investigated:

As a function of frequency, the transducer can be approximated by either a spherical source or a plane piston in an infinite baffle. The former applies when the wavelength of the signal is large compared to the diameter of the transducer; the latter, when the wavelength is small by comparison.

The ratio of the pressure to the velocity at the surface of a spherical source (the specific acoustic impedance) is given by

$$\frac{p}{u} = z = \rho c \frac{k^2 r^2}{1+k^2 r^2} + j \rho c \frac{kr}{1+k^2 r^2}$$

where k equals ω/c and r is the radius of the sphere [11]. When approximated by a spherical source with velocity u, the transducer has an effective radius of a/2 [11], so that the transducer radiation impedance Z_r is given by

$$Z_r = A\rho c \left[\frac{k^2 a^2}{4+k^2 a^2} + j \frac{2ka}{4+k^2 a^2} \right]$$

The area of the transducer enters this expression because Z_r is defined in terms of force and velocity, rather than pressure and velocity as in the case of the specific acoustic impedance.

When the wavelength is small compared to the diameter of the transducer, the radiation impedance can be approximated by that for a piston in an infinite baffle,

$$Z_r = A\rho c \,(R_1 + j X_1)$$

where R_1 and X_1 are the two piston impedance functions defined respectively as [10,11]

$$R_1 = 1 - \frac{J_1(2ka)}{2ka}$$

where $J_1(2ka)$ is the Bessel function of order one and argument 2ka

and

$$X_1 = \frac{4}{\pi}\left[\frac{2ka}{3} - \frac{(2ka)^3}{3^2 \cdot 5} + \frac{(2ka)^5}{3^2 \cdot 5^2 \cdot 7} - \cdots\cdots\right] .$$

The transmitting characteristics of a transducer whose parameters have the nominal values

radius = 1 cm

stiffness = 10^7 N/m

mass = 5 X 10^{-4} kg

ϕ = 10^{-3} N/V

blocked capacitance = 300 pF

input voltage = 1 V

can be demonstrated by approximating Eq. 2-10 in three frequency ranges:

(1) At very low frequencies, where ka<<1, the impedance will be dominated by the mechanical stiffness of the transducer. In this region, 2-15 is approximated by

$$|P| \approx \omega^2 \cdot \frac{\rho a^2 \phi}{2s} \tag{2-16}$$

from which it can be seen that an increase in pressure output of 12 dB/octave can be expected.

(2) In the intermediate range, ka≈1, the real part of the radiation impedance is the dominant factor. In this region the transducer function can be approximated by

$$|P| \approx \omega \cdot \frac{\phi}{2\pi c} \tag{2-17}$$

which indicates a source level increasing at a rate of six dB/octave.

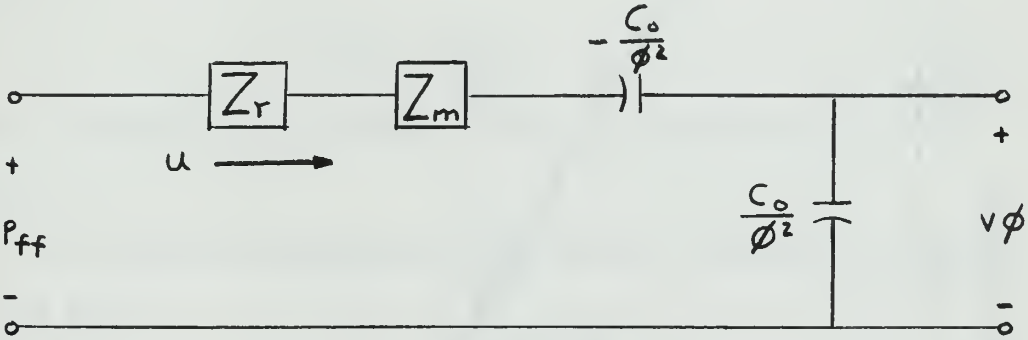
(3) The response in the high frequency, or mass controlled region, where ka>>1, is given by

$$|P| \approx \frac{\phi a^2 \rho}{2m}, \tag{2-18}$$

a response whose magnitude is independent of frequency.

Figure 6 is an asymptotic representation of the above approximations in which the three distinct areas of frequency dependence are readily apparent.

As a receiver, the foil is set in motion by an impinging sound pressure wave. Figure 7 shows the equivalent circuit of the trans-



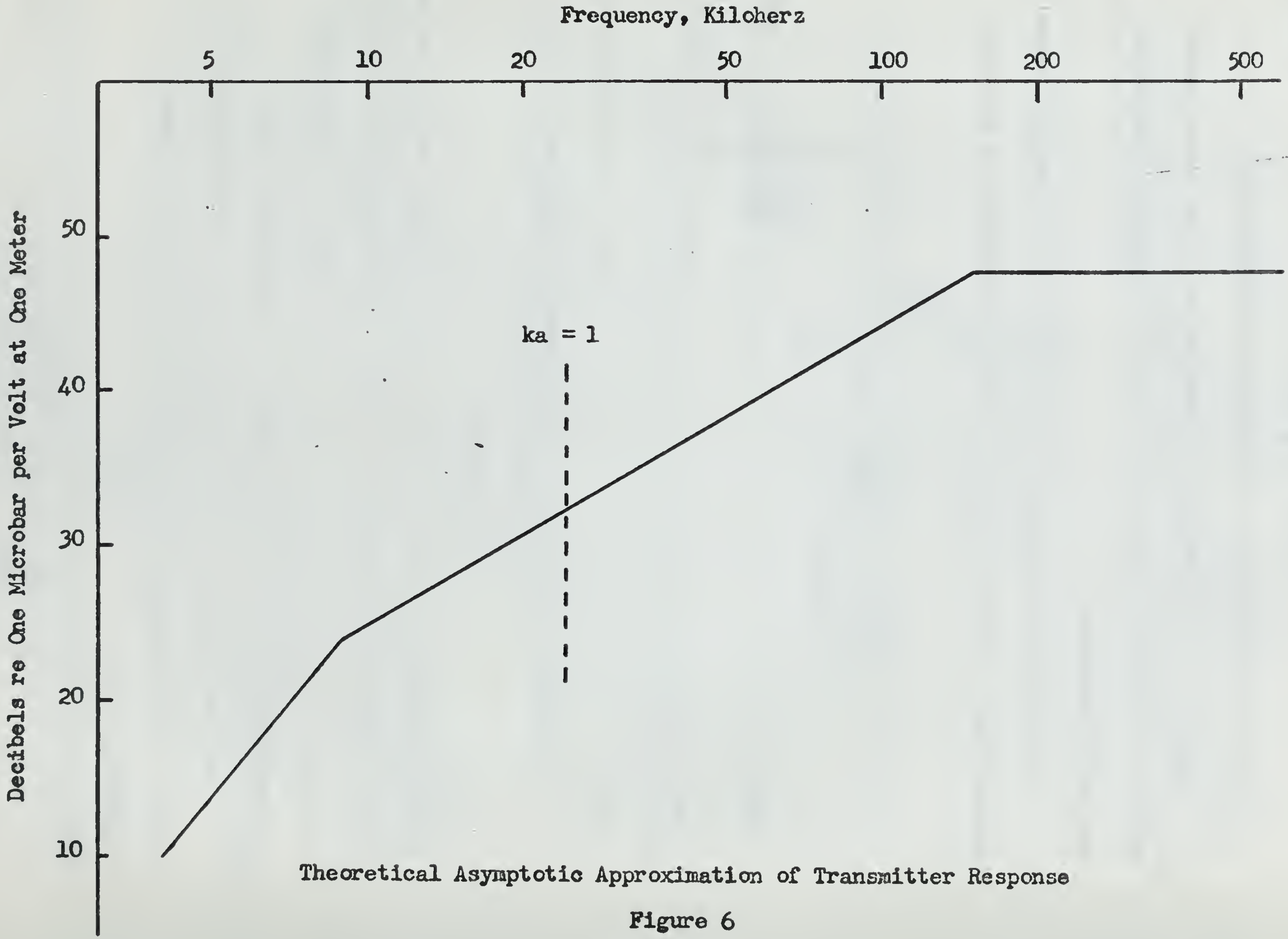
Equivalent Circuit for an Electrostatic Transducer
in the Receiving Mode

Figure 7

ducer [2] where p_{ff} is the free field sound pressure, defined as the sound pressure level existing at a point in the medium prior to the introduction of the receiver at that point, and it is assumed that the pressure wave is incident normal to the transducer face.

The open circuit voltage developed at the right-hand port is a result of the voltage divider action across the shunt capacitor C_o/ϕ^2 so that

$$\frac{v}{P_{ff}} = \frac{\pi a^2 \phi}{j\omega C_o (Z_r + Z_m)} \tag{2-19}$$



Theoretical Asymptotic Approximation of Transmitter Response

Figure 6

The receiving characteristics of the same transducer can be approximated by again assuming three frequency conditions:

(1) When $ka \ll 1$, the magnitude of the open circuit voltage developed for a unit value of free field pressure in the medium is

$$|V| \approx \frac{\pi a^2 \phi}{C_o s} , \tag{2-20}$$

a response which is independent of frequency.

(2) Within the limits of the mid-frequency approximation, $ka \approx 1$,

$$|V| \approx \frac{\phi}{C_o \rho c} \cdot \frac{1}{\omega} \tag{2-21}$$

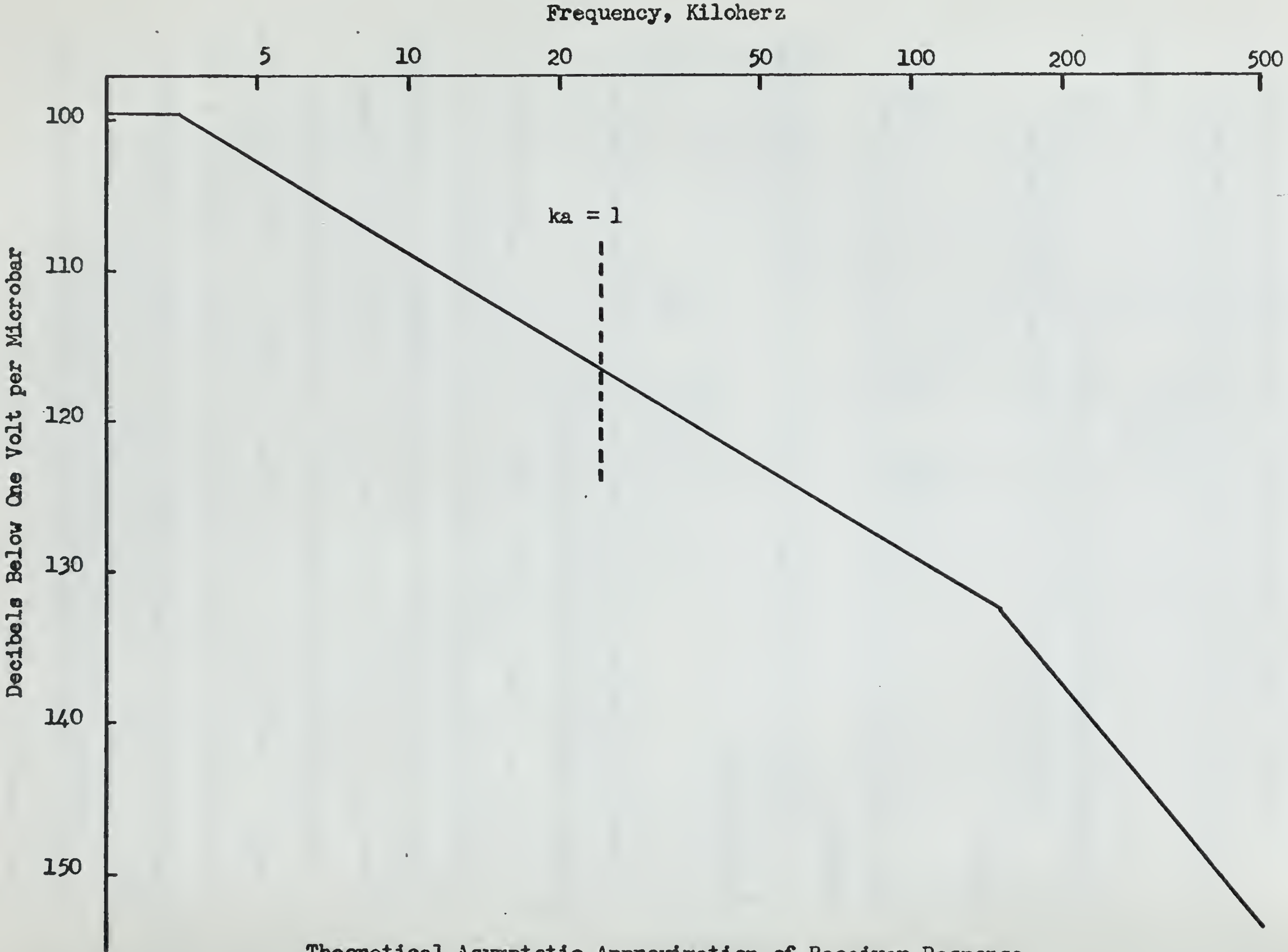
and a fall-off in open circuit voltage of six dB/octave can be expected.

(3) Under the approximation that $ka \gg 1$, a loss of 12 dB/octave occurs since

$$|V| \approx \frac{\pi a^2 \phi}{C_o m} \cdot \frac{1}{\omega^2} . \tag{2-22}$$

An asymptotic curve of these approximations utilizing the nominal values previously given is shown in Fig. 8.

It can be seen from Fig. 6 that, within the frequency range 9-150 kHz and with constant voltage applied to the transducer, the source level will increase linearly with frequency. A similar transducer used as a receiver will then show a constant output voltage since its sensitivity decreases with increasing frequency in this range. A combination of transmitter and receiver of this type therefore represents a two-port network whose transfer function is a constant within this frequency range. This is especially advantageous for experiments utilizing pulsed oscillations since the input will merely be changed in magnitude after having been passed through the two transducer system.



Theoretical Asymptotic Approximation of Receiver Response

Figure 8

3. Determination of Parameters

The parameters upon which Figs. 5 and 7 are based were determined for each transducer so that the performance of any given one could be predicted by use of the transfer functions 2-15 and 2-19. This was necessary because the transducers were handmade and differed from each other in small but significant details.

Some of the parameters were determined directly through experimentation. Others were deduced from the physical characteristics of the transducer itself and then verified by experimental data.

This section describes how the parameters were determined, whether through direct measurement, or through physical reasoning. The results of attempting to verify those parameters whose values were theoretically determined are described in Section 5.

Blocked Capacitance (C_o)

The value of the blocked capacitance was determined using a Dranetz Complex Impedance Admittance Meter, Model 100-B, set up as shown in Fig. 9. With the transducer in water, the impedance of the

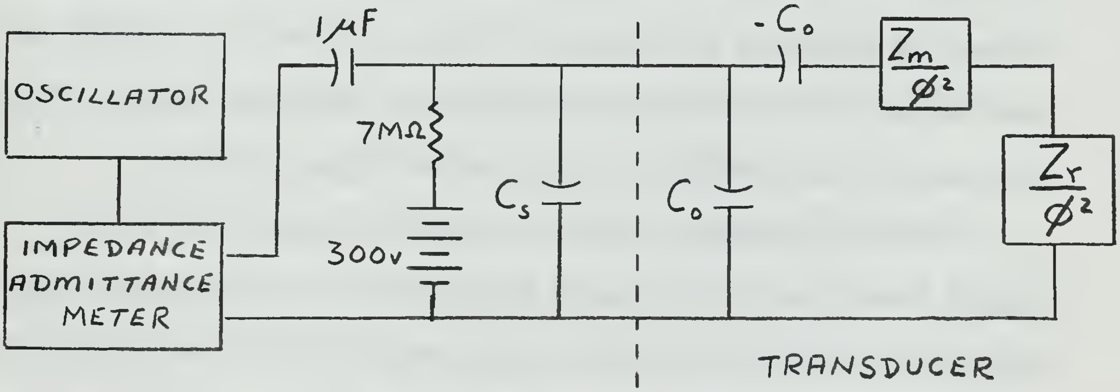


Diagram of Electronics used to Measure
Blocked Capacitance

Figure 9

motional branch is quite large. For example, the transducer shown in Figs. 6 and 8 has a motional branch impedance in water of approximately $500\,M\Omega$ for ka = 1 while the impedance of the electrical branch is only about $7\,k\Omega$. It can then be seen that for $ka \geq 1$, the motional branch is effectively an open circuit and the susceptance measured by the meter will be due to the sum of the stray capacitance (leads, holder, etc.) and C_o. The usual relationship between susceptance and capacitance will then yield the total capacitance from which can be subtracted the stray capacitance (measured separately using the same set-up as Fig. 9 with the transducer removed from the holder) leaving the blocked capacitance as the result.

With the relationship given by 2-7a, the equilibrium distance between the plates with the bias applied, x_o, can be determined. This quantity will in turn permit the calculation of $\emptyset$, the turns ratio of the ideal electromechanical coupling transformer, by use of Eq. 2-13.

Mechanical Stiffness

The mechanical stiffness (or compliance) of the system can be deduced by examining the mechanism which provides "the spring" as the foil is incrementally displaced by the impinging pressure or, in the case of a transmitter, by the applied signal voltage.

Since the backplate cannot be perfectly smooth (in a microscopic sense), there will exist small pockets of air entrapped between the backplate and the foil when the foil is forced against the backplate by the biasing voltage. These air pockets provide the spring against which the diaphragm works.

It is reasonable to assume that the heat generated in compressing this trapped air is transmitted to the aluminum backplate so that the temperature of the air remains constant. This assumption of an isothermal compression leads to the equation of state

$$PV = \text{Constant}$$

and

$$\Delta P = \frac{P_o}{V}\,\Delta V = \frac{P_o}{Ad}\,Ax = \frac{P_o x}{d}\,.$$

The restoring force due to the entrapped air can be expressed as

$$f = \frac{P_o A}{d}\,x$$

so that the mechanical stiffness, s, is given by

$$s = \frac{P_o A}{d}$$

From the above discussion it can be seen that the stiffness of the transducer can be readily affected by changing the thickness of the air gap. The method chosen was to roughen the surface of the backplate by the use of grinding compounds. (Another method that has been used is the cutting of concentric grooves in the backplate [5]. This method was not used here as it was desired to determine some effective air gap thickness as a parameter. In the case of a randomly roughened surface, there would exist a relatively uniform gap, whereas in the case of grooves the effective air gap would vary across the face.) Since increasing the roughness of the surface will increase x_o, the sensitivity will be decreased.

The contribution of the film itself has been neglected in deriving an expression for the mechanical stiffness. This was done to simplify the discussion but was also based on the premise that the stiffness of the mylar was much smaller than that of the entrapped air and could reasonable be ignored. The validity of this position is discussed in Section 5.

Implicit in previous discussion has been the assumption that the effective radius of the transducer is that of the backplate. Data to support this assumption are given in Table 3.

The mechanical mass initially was assumed to be the mass of that portion of the foil covering the backplate. Its value could then be calculated by multiplying the volume of this portion of the foil by the density of mylar, which is given as 1395 kg/m^3 [9]. The validity of this assumption as shown by analysis of frequency response characteristics is also discussed in Section 5.

The mechanical resistance, or damping, is associated with energy loss in the transducer itself. Attempts were made to measure it directly but without success. At low frequencies, it is swamped by the high impedance of the $-C_0$ term in the motional branch while at high frequencies it is dominated by the radiation resistance.

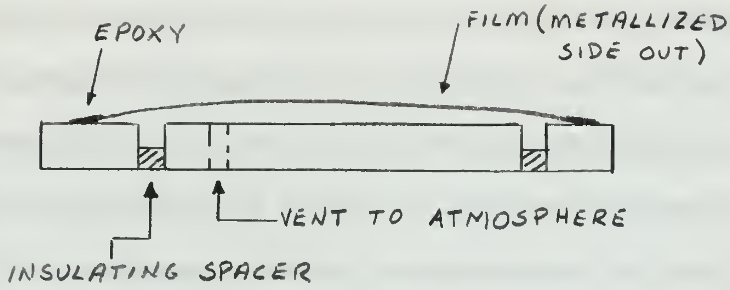
When $ka>1$, the real part of the radiation impedance becomes large, approaching $A\rho c$ in the limit. Since the radiation resistance is in series with the mechanical resistance, the latter may be neglected for $ka>1$. For small values of ka however, the radiation resistance decreases as $(ka)^2$, so that the mechanical resistance should become relatively large at some frequency.

It was assumed that ka would not decrease in the frequency range of interest to the point where the mechanical resistance would become a major part of the total resistance; thus, it could be neglected as a parameter affecting the operation of the transducer.

The validity of this assumption is discussed in Section 5.

4. Transducer Fabrication

The construction of a transducer is shown in Fig. 10. The



Details of Construction of a Mylar Transducer

Figure 10

design is simple, permits a very small air gap between the dielectric and the backplate (thus optimizing sensitivity), and is suitable for water immersion.

MYLAR, a DuPont registered trademark polyester film with a dielectric constant of 3.0-3.2 in the frequency range 1 kHz-10 MHz [7] was used as the diaphragm. This film is manufactured in varying thicknesses with either an aluminum or gold coating on one surface. For purposes of this project, one mil aluminum-coated foil was used.

The backplate is made of quarter-inch aluminum plate; the radius of the inner disk is that desired for the transducer, the radius of the outer disk was 1.25 inches. The surface of the backplate was polished to aid in increasing sensitivity. As was described in Section 3, some transducers were prepared with roughened surfaces.

The inner disk is fitted into the outer ring with an insulating spacer recessed on one side to provide a well between the inner and outer sections. A small (0.5mm. diam) hole is drilled through the inner disk to allow venting to the atmosphere when the foil is drawn against the backplate by the biasing voltage. Losses due to the presence of this opening are considered negligible since even at frequencies as high as five MHz the diameter of the hole is less than a wavelength.

A piece of foil, larger than the inner electrode, is centered on the backplate with the metallized side out. Care must be taken to ensure that no particles of dust or other foreign matter are between the foil and the backplate as their presence results in lowering the sensitivity which could be achieved by the otherwise narrow air gap.

A thin strip of epoxy adhesive is then applied around the edge of the foil to form a water-tight seal. After the epoxy has cured sufficiently, silver conducting paint is applied to several places on the foil and backplate to provide a conducting path between the metallized surface of the film and the backplate. When the silver paint has dried, the transducer is complete and ready to mount in a suitable holder which will permit the application of the necessary voltages, hold the transducer rigid, and permit immersion in water.

A serious problem was encountered in using transducers made as described above:

After a short period (about one hour) of use in water with the normal bias voltage of 300 volts applied, it was observed that the sensitivity decreased substantially. Examination of the transducer revealed that the aluminum coating of the foil was disappearing. The resistance of the conducting path increased from a few ohms to several kilohms. The fact that this erosion began adjacent to the spots of silver conducting paint suggests that the mechanism responsible for this erosion was an electrolytic action between the silver and the aluminum.

Based on this, it was felt that isolating the silver and aluminum from direct contact with the water without affecting the mechanical contact would provide a solution to the problem. Initial attempts involved smearing the surface of the transducer with a thin coating of petroleum jelly. It was found that this technique retarded the action but did not eliminate it. The entire face of the transducer was then coated with liquid neoprene. This proved highly effective in eliminating the erosion but introduced two different problems:

(1) It was not possible to achieve a uniform coating without sophisticated application methods. This resulted in a non-uniform distribution of mass across the face of the transducer causing an imbalance of accelerations at high frequencies.

(2) The mass added by the neoprene to that of the mylar is unknown. Thus, the frequency at which the mass reactance begins to dominate cannot be predicted. The total mass can be determined by cutting away that portion of the diaphragm covering the inner electrode and weighing it on a balance. This method was used for one of the experiments but since it destroys the transducer, is not of value in predicting the frequency response of a particular transducer.

These disadvantages suggested covering the aluminum face of the foil with a substance of uniform thickness and known density. Since it was also desired to lower the frequency at which the mass begins to dominate to one within the frequency range of the electronics equipment used in determining frequency responses, brass shim metal was used as the coating. A circular wafer of metal was cut, a drop of epoxy adhesive placed on the mylar film and the brass wafer placed over the transducer face. The wafer was weighted down while the epoxy cured to insure bonding across the entire face.

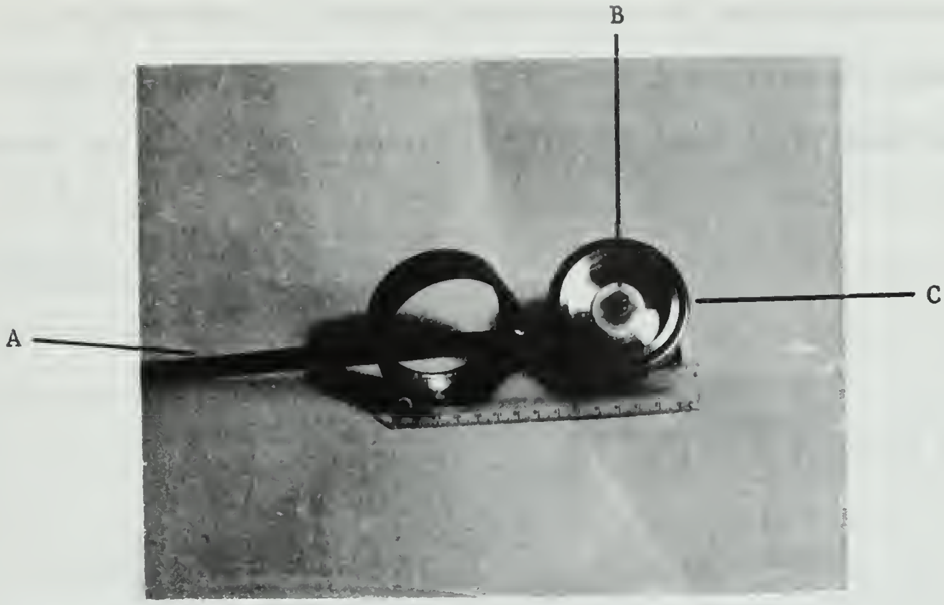
The holder used in these experiments is shown in Fig. 11. Coaxial cable is passed through the copper tube (A), electrical contact being made between the shield of the cable and the tube. The tube is joined to the holder with watertight fittings with provision made for the air chamber of the holder to vent to the atmosphere through the tubing. The center conductor of the cable is soldered to the copper spring (B) which makes contact with the inner electrode of the transducer. The transducer is placed with its back on the O-ring (C) which seals the air chamber and then the retaining ring is screwed on.

Figure 12 shows the holder fully assembled with a neoprene coated transducer installed ready for use in water.

5. Experimental Results and Conclusions

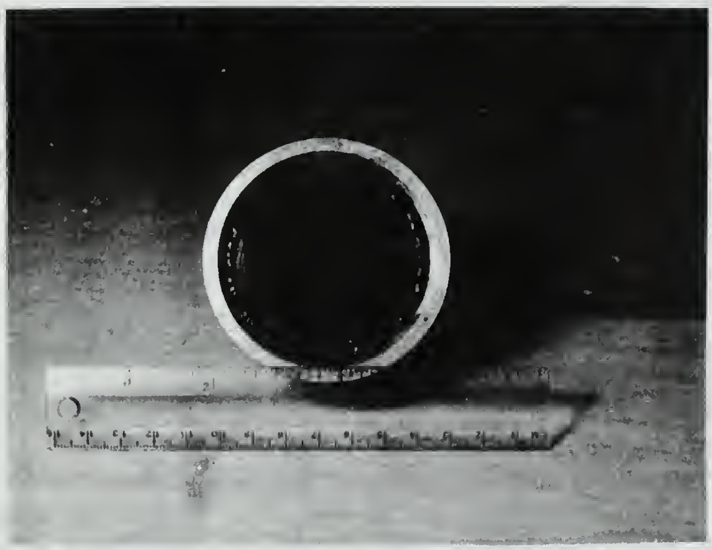
Various experiments were conducted with the mylar transducers to obtain data which would (1) provide experimental verification for theoretically determined parameter values; (2) show that the equivalent circuits and their associated transfer functions are valid representations of a transducer as transmitter and receiver; and (3) justify the assumption that the transducer acts as a plane piston in an infinite baffle for $ka >> 1$. For ease of presentation, the experiments conducted and the results obtained will be discussed along these three lines.

Most of the experiments were conducted in an unlined and electrically ungrounded tank 75 x 75 x 90 cm deep. Using a reverberant tank required use of pulsed signals so that the direct signal could be distinguished from reflections.



Disassembled Transducer Holder

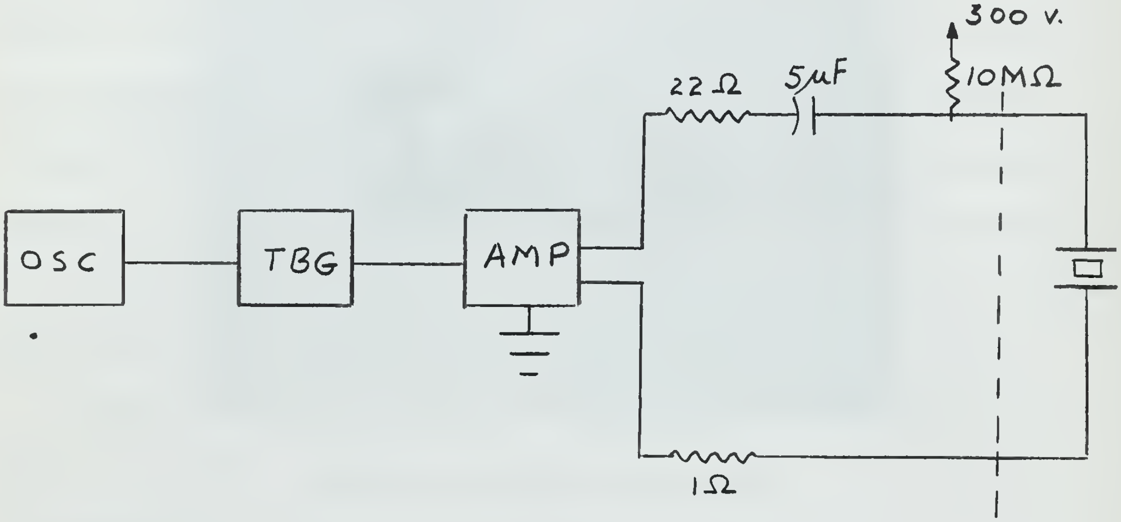
Figure 11



Transducer Holder with Transducer Installed

Figure 12

Figure 13 is a block diagram of the electronics used to drive the transducers. The oscillator (Hewlett-Packard Model 650A Test Oscillator) provides the signal which is gated in the tone burst generator (General Radio Model 1398A) and passed through a Hewlett-Packard Model 467A Power Amplifier. The main purpose of the amplifier

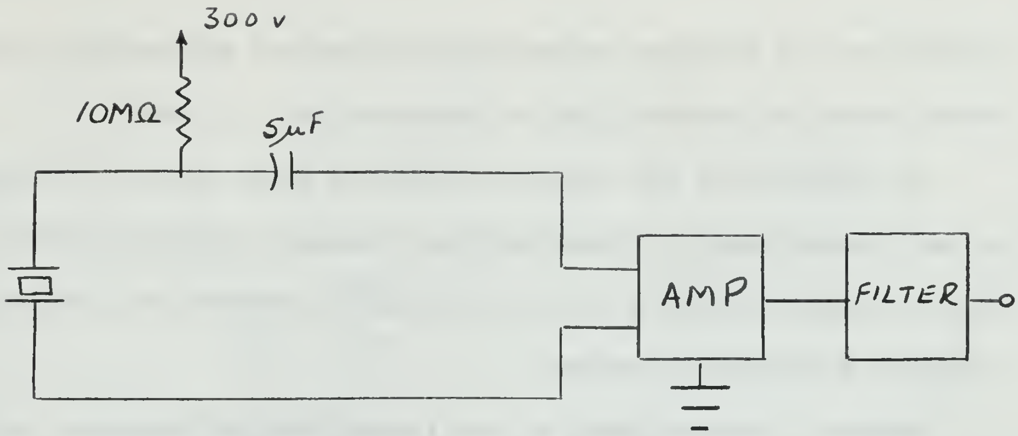


Block Diagram and Schematic of Transmitter

Figure 13

is to provide a signal source of low impedance, nominally one milli-ohm, to match the low impedance of the transmitter at high frequencies. The 22 ohm resistor is provided to damp out any parasitic oscillations which may be generated due to the pulse excitation. The five micro-farad capacitor and ten megohm resistor are used to block the dc and ac respectively while the one ohm resistor acts as a current sampler. The dc bias voltage is provided by a battery or alternatively, when a variable bias is required, by a Hewlett-Packard 712A Power Supply.

Figure 14 shows the electronic equipment used with the transducer acting as a receiver. The signal is amplified 40 dB in a Tektronix Type 1121 amplifier whose one megohm input impedance provides the means of measuring open circuit voltages. The filter used was an SKL Model 302 Variable Electronic Filter.



Block Diagram and Schematic of Receiver

Figure 14

In obtaining data for the receiver response characteristic, the transducers were calibrated by the reciprocity method [11] in the frequency range 5-500 kHz with a precision of $\pm$ 1.6 dB.

Two transducers, the one to be calibrated and a reversible one, were placed successively at the same point in an arbitrary sound field. The ratio of the output voltages of these two transducers is the ratio of their microphone sensitivities. Then, the reversible transducer was used as a transmitter and the one to be calibrated as a receiver. The transmitter was excited by a constant voltage input and its current and the open circuit voltage of the receiver were measured as a function of frequency. From the ratio of the receiver voltage to the transmitter current, the sensitivity ratio, and the reciprocity constant, the receiver sensitivity was determined.

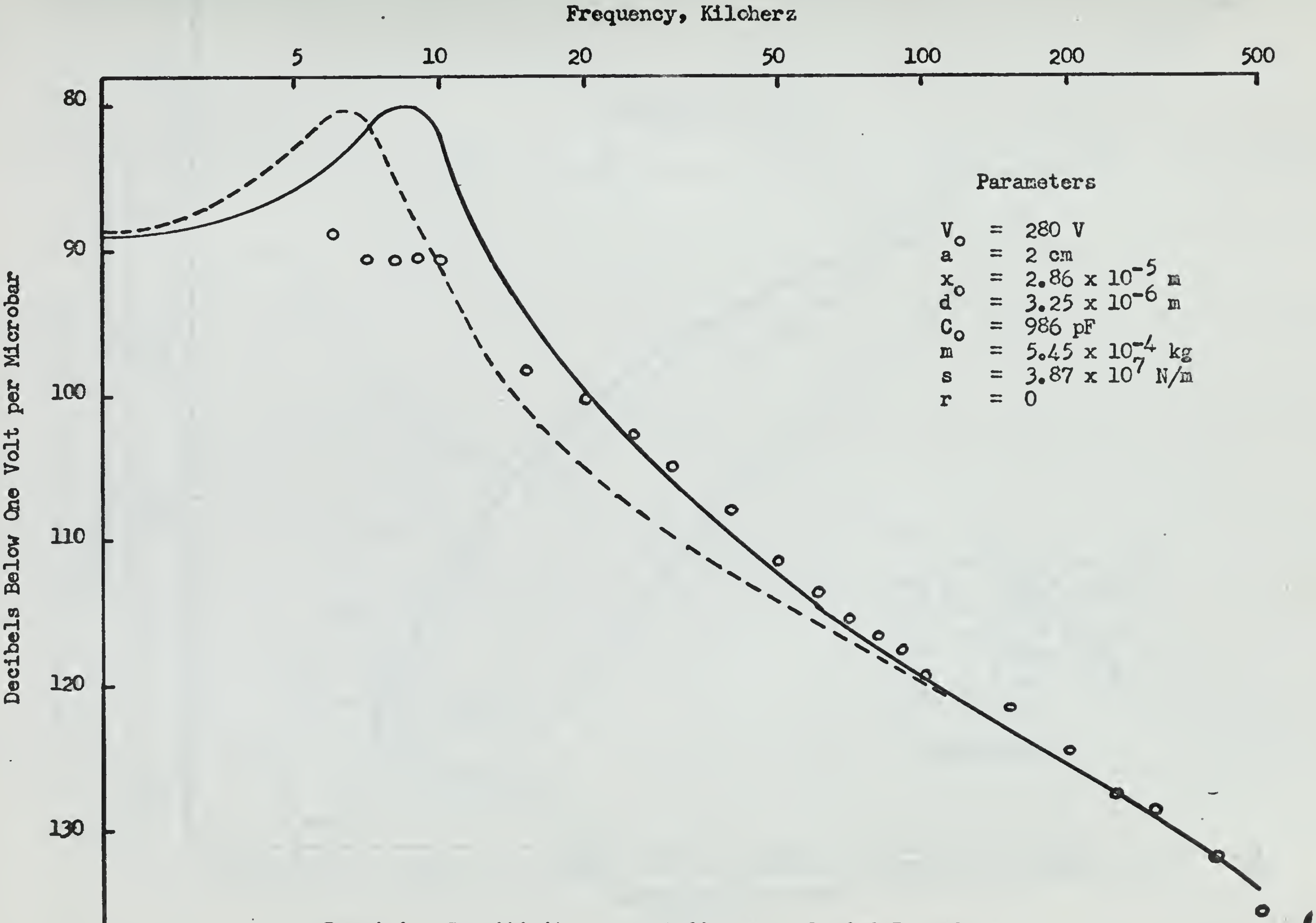
Placing a calibrated hydrophone in the sound field of a transmitter while the signal frequency is varied and the transmitter voltage remains constant, enables the free-field pressure at the hydrophone to be measured as a function of frequency. After correcting for the distance between the transmitter and receiver, the source level was obtained with a precision of $\pm$ 1.8 dB.

The validity of the transfer functions given by 2-15 and 2-19 is best demonstrated by comparing the frequency response predicted by the transfer function for a particular transducer with the experimentally determined response.

Computer programs based on the transmitter and receiver functions were developed and are contained in Appendix I. These programs will print out the magnitude and phase of the source level, or the open circuit voltage, for a unit magnitude input as a function of frequency, given the necessary transducer parameters.

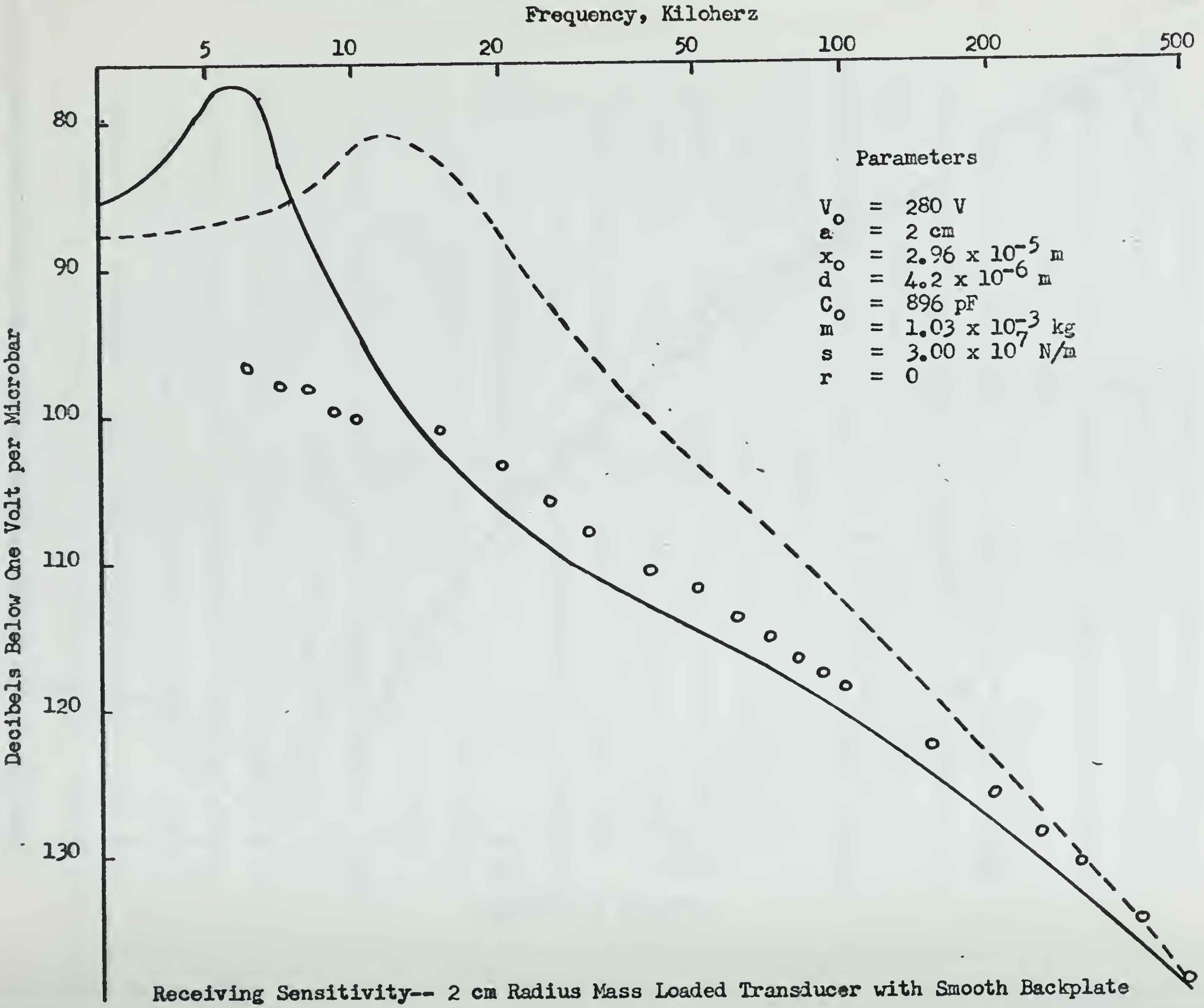
Figures 15, 16, and 17 are plots of receiver sensitivity as determined by the computer program for three transducers with varying parameters. The solid curve is based on the radiation impedance of a piston while the dashed curve is based on the radiation impedance of a simple source. The data were obtained by calibrating each of the transducers as previously described.

The data correlate reasonably well with the predicted response curve for frequencies greater than 20 kHz. The general validity of the receiver transfer function and the model and assumptions on which it is based is demonstrated in these figures. As can be seen in the curves however, the validity of those parameters which determine the low frequency response is somewhat questionable. Reference to Eq. 2-19 shows that these parameters are: radiation impedance, mechanical resistance, and stiffness. The radiation impedance for a sphere or a piston can be computed precisely for any given frequency and this is accomplished in the computer program. However, for a two centi-



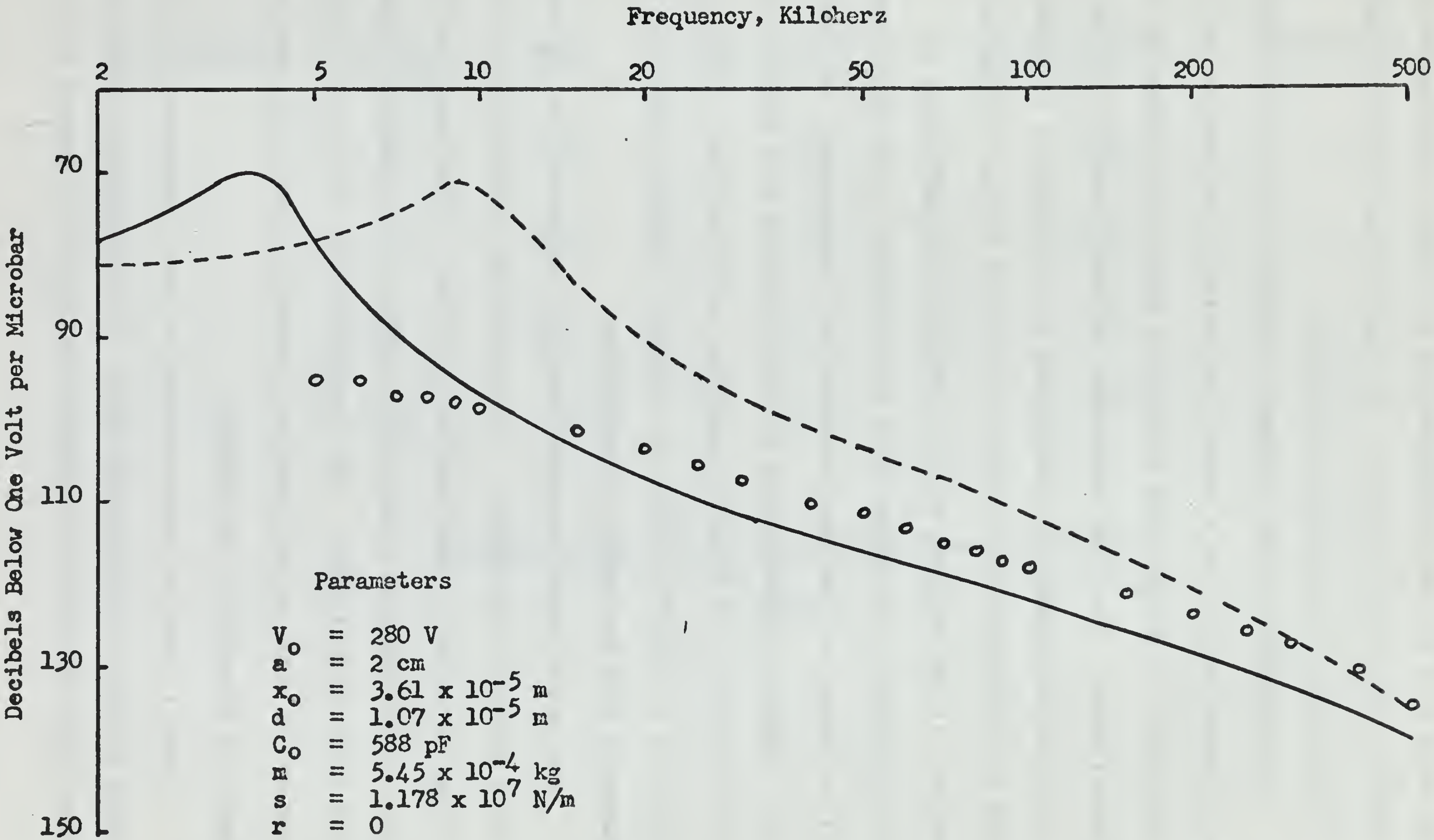
Receiving Sensitivity--2 cm Radius Mass Loaded Transducer

Figure 15



Receiving Sensitivity-- 2 cm Radius Mass Loaded Transducer with Smooth Backplate

Figure 16



Receiving Sensitivity--2 cm Radius Mass Loaded Transducer with Roughened Backplate

Figure 17

meter radius transducer, ka equals unity at about 11 kHz so that in the range 5-20 kHz the transducer can be closely approximated by neither a sphere nor a piston. As a result, the radiation impedance in this range is not readily calculable.

The magnitude of the stiffness parameter has been determined only theoretically. As a result, its value is in question and it is appropriate to justify this theoretical value of stiffness by experimental means. The first experiment conducted towards this end involved the measurement of susceptance as a function of frequency with the transducer in a vacuum to eliminate medium loading as a factor. It was expected that as resonance was approached the $B = j\omega C_0$ curve would depart from its linearity in the usual manner [11] allowing the resonant frequency to be determined, and from it s/m. However, the parameters of the transducer were such that any deviations from the linear susceptance curve were very slight and difficult to discern, making the resonant frequency impossible to determine with any degree of confidence.

The second method involved using two transducers in air separated by about 20 centimeters. It was reasoned that the open circuit voltage developed by the receiver would peak at the mechanical resonance of the receiver since medium loading at the expected frequencies would be negligible. The transmitter was excited by a pulsed sinusoid in order to eliminate the formation of standing waves between the transmitter and receiver.

Table 1 gives the data obtained for four transducers with differing values of stiffness and mass. The magnitudes of these parameters were determined as described previously in Section 3. The

Transducer	Stiffness (10^6 N/m)	Mass (10^{-5} kg)	$\omega_0 = (s/m)^{\frac{1}{2}}$ (10^5 radians/sec)	ω_0 (Observed) (10^5 radians/sec)	Discrepancy (percent)
1	2.71	1.11	4.94	3.83	22
2	4.56	1.66	5.28	5.24	0.8
3	11.8	54.5	1.47	2.02	37
4	7.85	1.66	6.86	6.60	3.8

Experimental Verification of the Stiffness-Mass Ratio

Table 1

experimental data is in general agreement with the theoretical values and, anticipating independent verification of the mass, it can be concluded that the theoretical assumptions concerning mechanical stiffness are essentially correct.

There remains only the mechanical resistance. The assumption was made that in water the mechanical resistance was much less than the resistance provided by the medium and consequently could be neglected. It is necessary to show that this is justifiable.

One way to determine mechanical resistance is through the quality factor, Q, of a system given by

$$Q = \frac{\omega_0 m}{R_m} = \frac{\omega_0}{\omega_2 - \omega_1}$$

where R_m is the mechanical resistance of the system and ω_2 and ω_1 are the frequencies at which the voltage has dropped to 0.707 of its value at resonance.

Using the data from which the stiffness-mass ratios of Table 1 were obtained, ω_2 and ω_1 can be determined. Since for a transducer, $R_m = \mathrm{Re}(Z_r + r)$, the mechanical resistance of the transducer, r, can be computed by simple substitution. Results are presented in Table 2.

Transducer	Q	mass (10^{-5} kg)	Re Zr (kg/sec)	r (kg/sec)
1	1.82	1.11	.13	2.2
2	1.16	1.66	.13	7.4
3	1.475	54.5	.52	75.0
4	1.15	1.66	.13	9.4

Experimental Determination of Mechanical Resistance

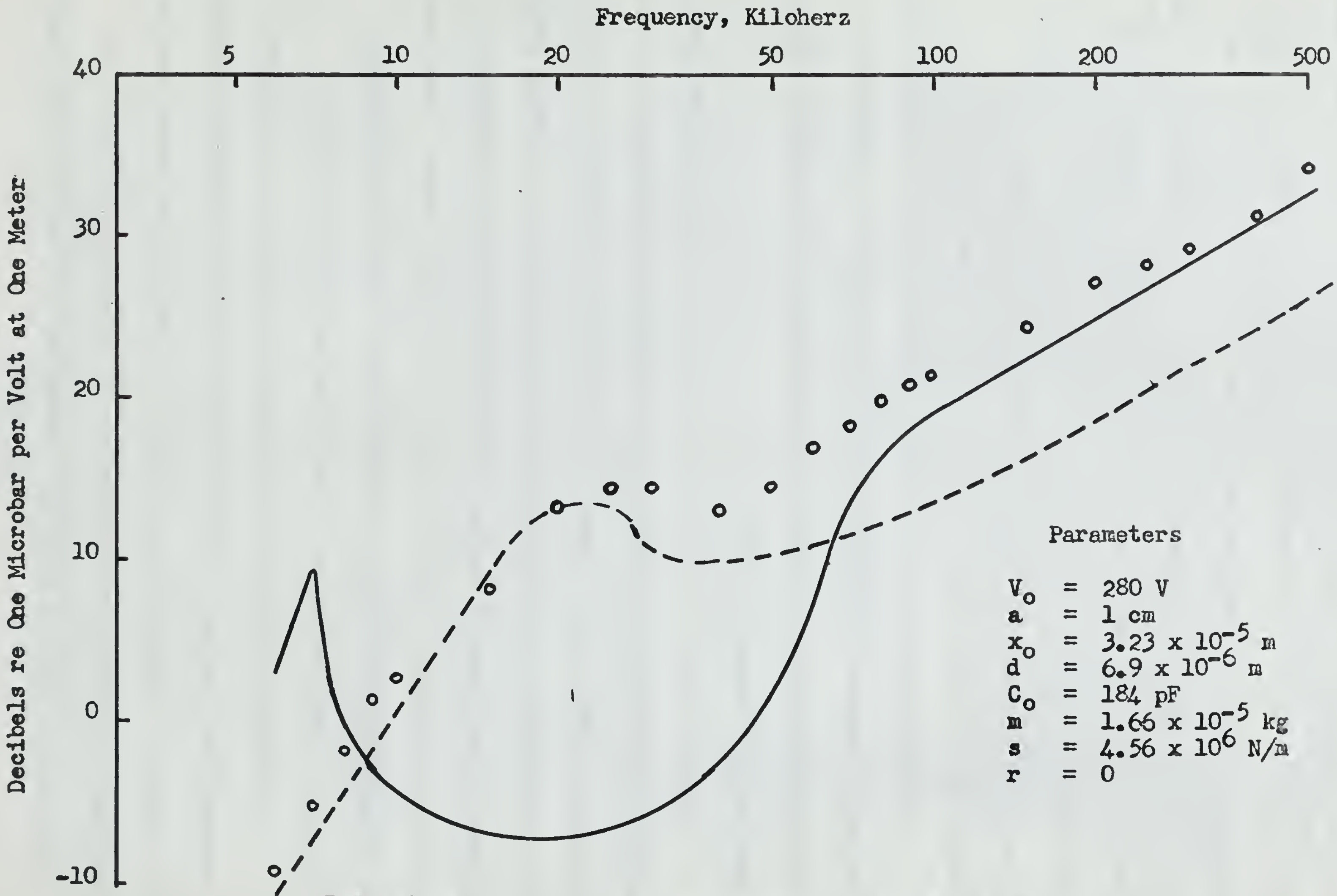
Table 2

The resistances are quite small except in the case of transducer 3, although 75 mechanical ohms is only 4 percent of the value of radiation resistance in water at frequencies greater than 30 kHz. Even at 10 kHz, where the data exhibits its greatest deviation from the computed curve, the radiation resistance is still an order of magnitude greater than the mechanical resistance so that neglecting it has little effect. It should be noted that transducer 3 differed from the others by having a brass wafer attached to the mylar face. It is conceivable that this introduced additional resistance due to a flexing of the brass wafer as it was driven by the force field.

It appears then that the transfer function fails to predict the frequency response when the wavelength approaches the dimensions of the transducer due to an inability to determine the radiation impedance in this frequency range.

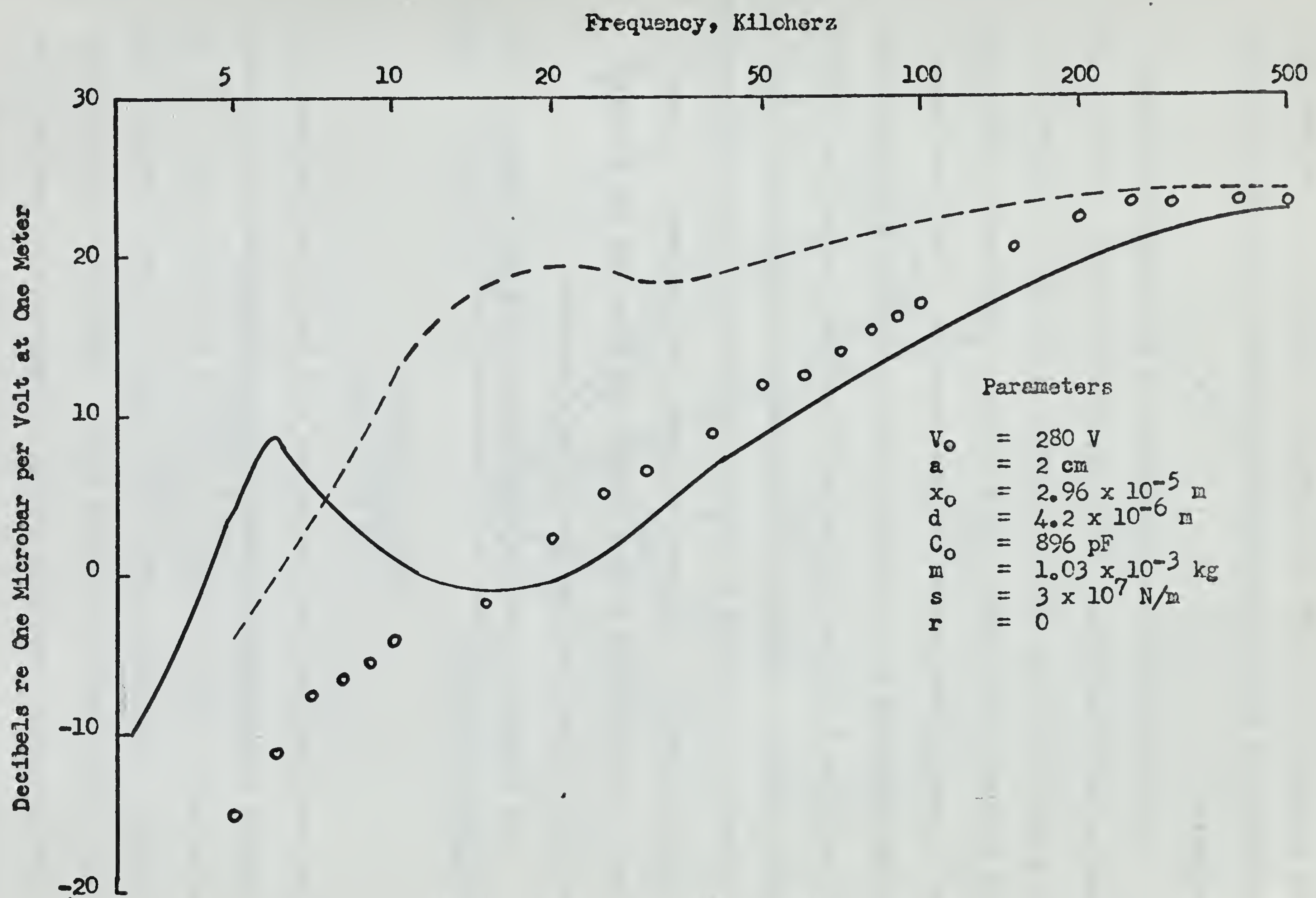
Figures 18 and 19 are plots of transmitter sensitivities determined by the computer program for two different transducers. As before, the solid curve is based on the radiation impedance of a piston source while the dashed curve is based on that of a simple source. In the higher frequency range, the transducer acts as a piston and in the low frequency range it appears as a simple source. When the wavelength approaches the dimensions of the transducer, however, there is a large deviation of data from the predicted curves.

In summary, it has been shown that the receiver and transmitter transfer functions are valid representations of the actual transducer but that the computer programs based on them are inaccurate when the wavelength approaches the dimensions of the transducer due to an inability to determine radiation impedance. It has also been shown



Transmitter Sensitivity--One Centimeter Radius Transducer

Figure 18



Transmitter Sensitivity—2 Centimeter Radius Mass Loaded Transducer

Figure 19

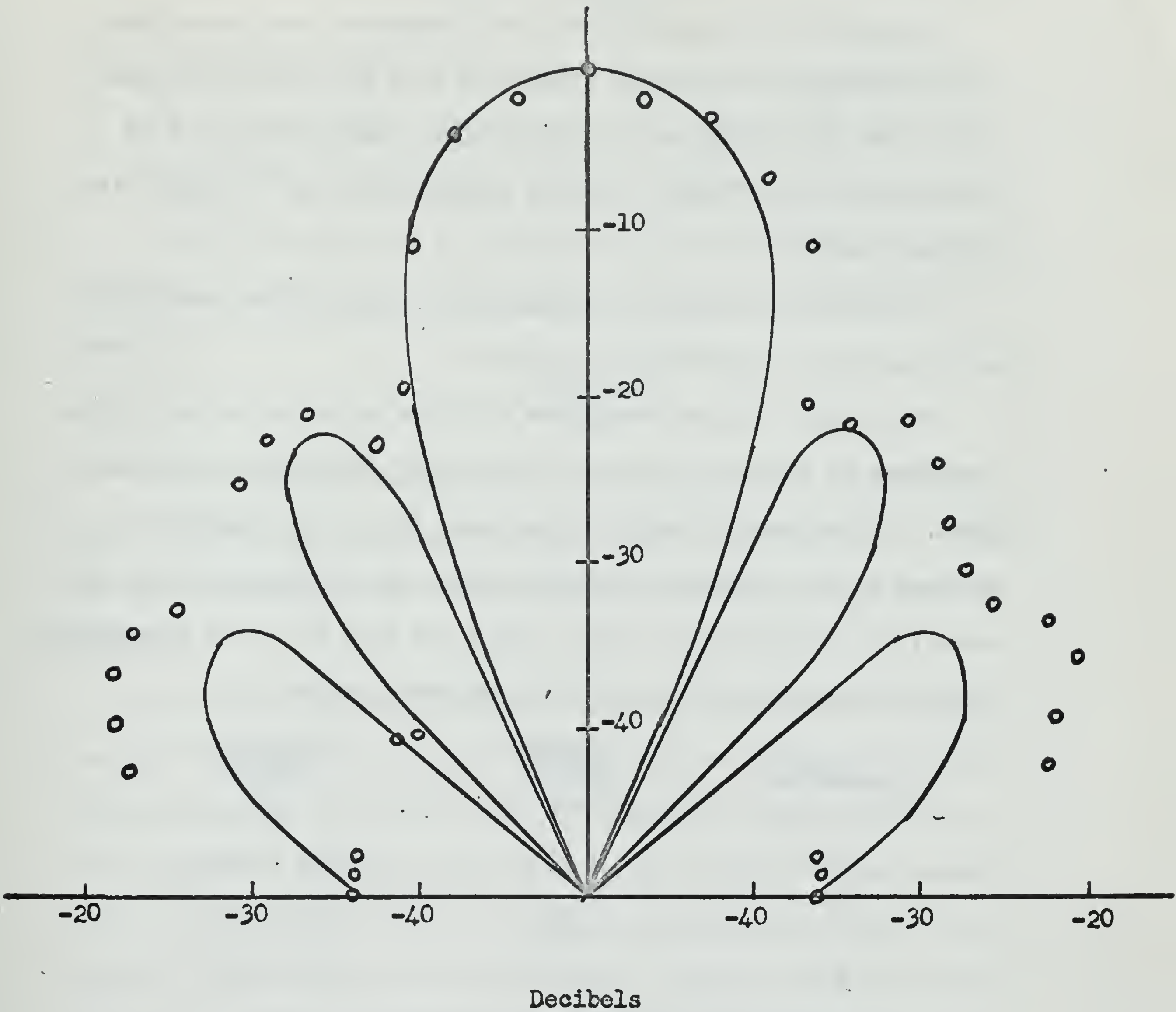
that the stiffness of the transducer is determined chiefly by the air gap between the foil and the backplate, and also that the mechanical resistance is much smaller than the radiation resistance and may be neglected.

On the basis of its construction, it is reasonable to expect that at short wavelengths the electrostatic transducer will operate as a piston with the familiar directional pattern of a major lobe and attendant minor lobes. This is not to imply that a uniform velocity exists across the face of the transducer. Since the surface of the backplate is not perfectly smooth, there must be many points at which the film makes contact with the backplate and the diaphragm has no velocity (assuming an incompressible diaphragm and a rigid backplate). It can be said though that the foil has some average velocity which is uniform in a macroscopic sense. This velocity is based in part on the effective air gap between the plate and the diaphragm and also on the effective area of the transducer.

The directivity pattern of a piston source is a result of the directivity term [11]

$$\frac{2J_1(ka \sin\theta)}{ka \sin\theta}$$

This term indicates that the pattern will have a null whenever the argument of the Bessel function results in the value of the function being zero. This will occur at values of ka sin θ = 3.83, 7.02, etc. Therefore, the angular width of the major lobe and of the side lobes can be determined for any value of ka. Figure 20 is a plot of the relative pressure output of a mylar transducer as a function of polar angle for ka = 9.8. The data correlate very well with the expected angular values, especially those for the angular width of



Directivity Pattern of One Centimeter
Radius Transducer

Figure 20

the major lobe and the first side lobes.

In addition to angular width, the directivity term specifies that the maximum of the first minor lobe will be 0.133 of the maximum of the major lobe, or, the first minor lobe will be 17.5 dB down from the major lobe. The data presented in Fig. 20 agree with this quite well.

It appears then that the assumption of piston-like operation of the transducer is supported by the data.

It has been implicitly assumed that the effective radius of the transducer is the same as that of the center electrode of the backplate. If the angular width of the major lobe of a transducer is measured at some frequency then the radius can be computed from the directivity function given above. This was done for three transducers of differing radii and the data are presented in Table 3.

TRANSDUCER	ASSUMED RADIUS (cm)	EFFECTIVE RADIUS (cm)
1	1.00	1.00 ± 0.01
2	1.83	1.87 ± 0.07
3	2.00	1.97 ± 0.08

Experimental Confirmation of Equality of Inner Electrode Radius and Effective Radius

Table 3

As was stated in Section 3, the mechanical mass was assumed to be that of the active volume of the diaphragm. In order to validate this assumption, use is made of the relationships

$$|P| \approx \omega \cdot \frac{\phi}{2\pi c} \tag{2-17}$$

and

$$|P| \approx \frac{\phi a^2 \rho}{2m} \tag{2-18}$$

The frequency for which Eqs. 2-17 and 2-18 become equal is

$$\omega = \frac{\pi a^2 \rho c}{m}$$

Then, the assumed value of the mechanical mass can be substituted in and the result can be compared with the frequency obtained from an experimentally determined transmitter response characteristic.

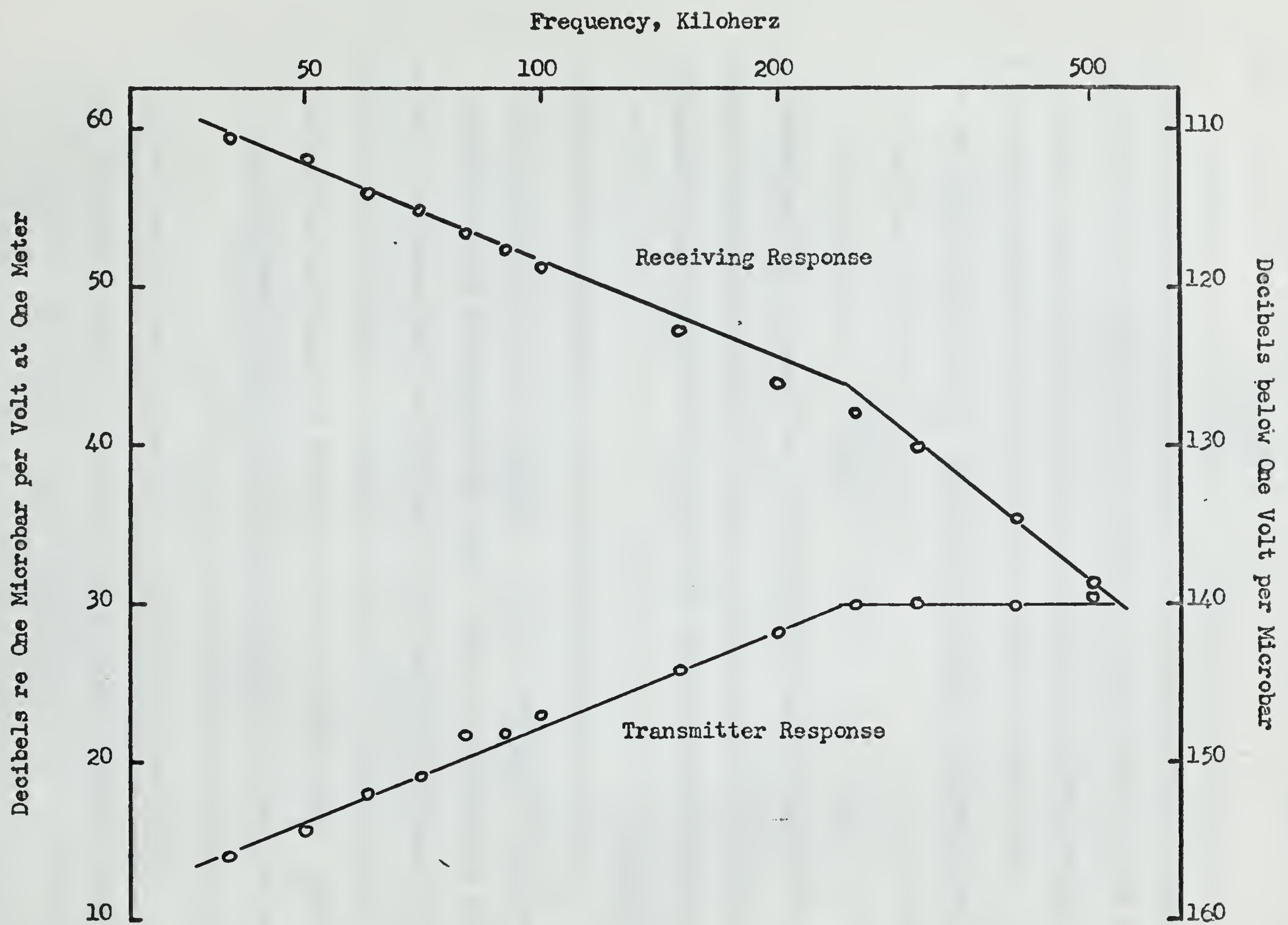
This frequency point is the same for the transducer acting as a receiver as well because equating 2-21 and 2-22 also yields the expression

$$\omega = \frac{\pi a^2 \rho c}{m}$$

As was discussed previously, it was necessary to increase the mass of the transducer face in order to bring the frequency at which the mass dominates within the bandwidth of the available electronic equipment.

The first experiment involved a two centimeter radius transducer with a brass wafer of 2.5 centimeter radius and two mil thickness attached to its face. Under the assumptions made concerning this parameter, the mass of the mylar-brass combination was calculated to be 5.90×10^{-4} kg, and a changeover frequency of 500 kHz predicted. Its response as a receiver and a transmitter was obtained and is presented in Fig. 21. Both curves show a rollover point of 240 kHz, an octave below the predicted value.

This transducer was poorly designed for the purpose of verifying an assumption based on the volume of the face adjacent to the inner electrode. As the brass wafer is relatively inflexible, it is reasonable to expect that the whole unit will be displaced thus increasing the mass accordingly. This was substantiated by weighing the diaphragm; its mass was 1.03 grams which when substituted in the



Frequency Response Characteristic of a Two Centimeter Radius
Mass Loaded Transducer

Figure 21

expression above gives a frequency of 285 kHz.

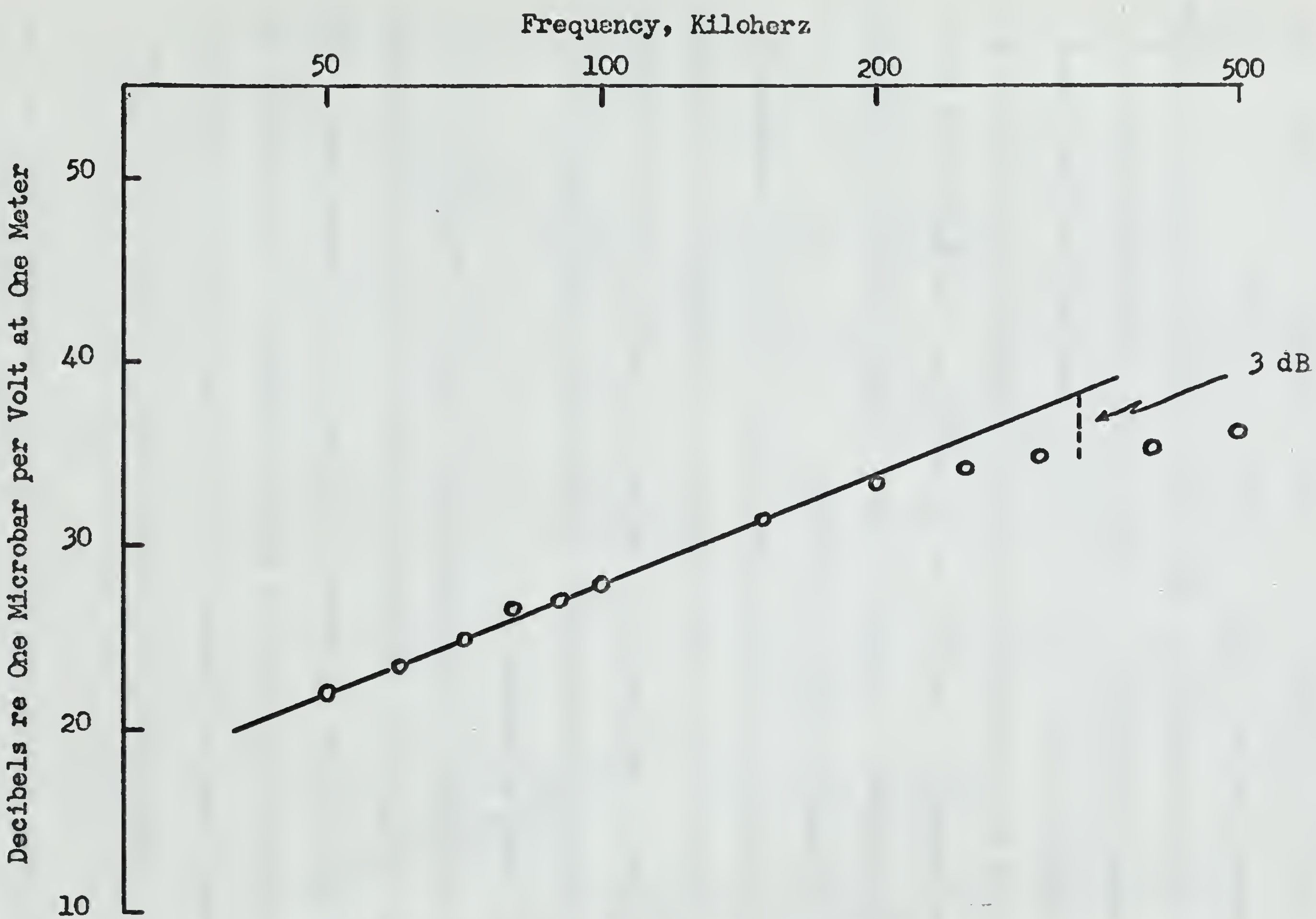
A 1.83 cm radius transducer with a two mil brass wafer of the same radius was made. The mass of this transducer was calculated to be 5.24×10^{-4} kg, predicting a roll-over frequency of 470 kHz. It was calibrated and the results are given in Fig. 22.

The corner frequency is not readily apparent although it appears to lie between 300-400 kHz. A more accurate determination can be made by using the fact that at the corner frequency the true curve differs from its asymptote by three dB. Extending the six dB/octave asymptote upward to a point three dB above the true curve will give the corner frequency. Figure 22 shows this extension of the asymptote and a break frequency of 335 kHz.

The actual and theoretical frequencies are better correlated than in the case of the first transducer. Whether or not the assumption involved in predicting the mechanical mass is valid is difficult to say from the above evidence; it seems safe to say that it is a reasonably good approximation.

This deviation of the assumed mass from the indicated mass of 29 percent brings in to question the previous experimental verification of the stiffness parameter. Decreasing the assumed mass by 29 percent increases the value of ω_0 by 16 percent. This change is not sufficiently large to discredit the conclusion that the stiffness is primarily determined by the air gap between the foil and the backplate.

Affecting the sensitivity of the mylar transducer are the bias voltage and the equilibrium distance between the diaphragm and backplate, x_o. Since the bias voltage is not a function of the transducer per se, and x_o, which is a function of the thickness of the mylar and



Transmitter Response of a 1.83 cm Radius
Mass Loaded Transducer

Figure 22

the roughness of the backplate, is not subject to variation with time, the sensitivity should be expected to remain reasonably stable.

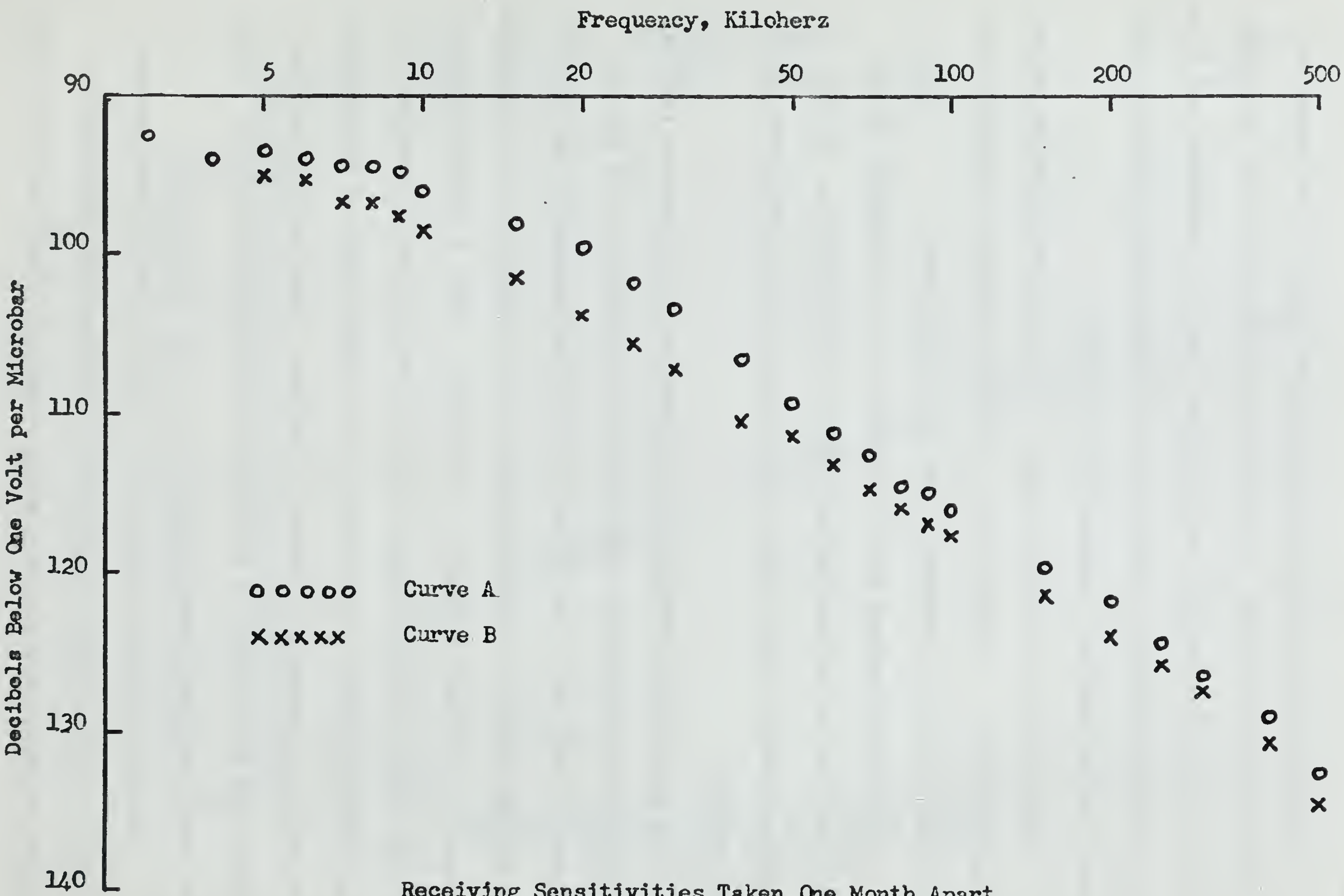
Figure 23 shows the receiving characteristic of one transducer taken at different times. The data for curve B were taken one month after the data for curve A, during which time the transducer was lying on a laboratory bench. Allowing for the imprecision of the data, the curves can be said to be approximately the same.

There is some difference between the curves though which should be accounted for. Assuming that x_o does not change, it appears that the bias voltage is responsible for this difference.

It has been assumed that the charge on the transducer is the result of the dc voltage applied and the capacitance C_o. If the bias were removed there would be no charge and the transducer would not function.

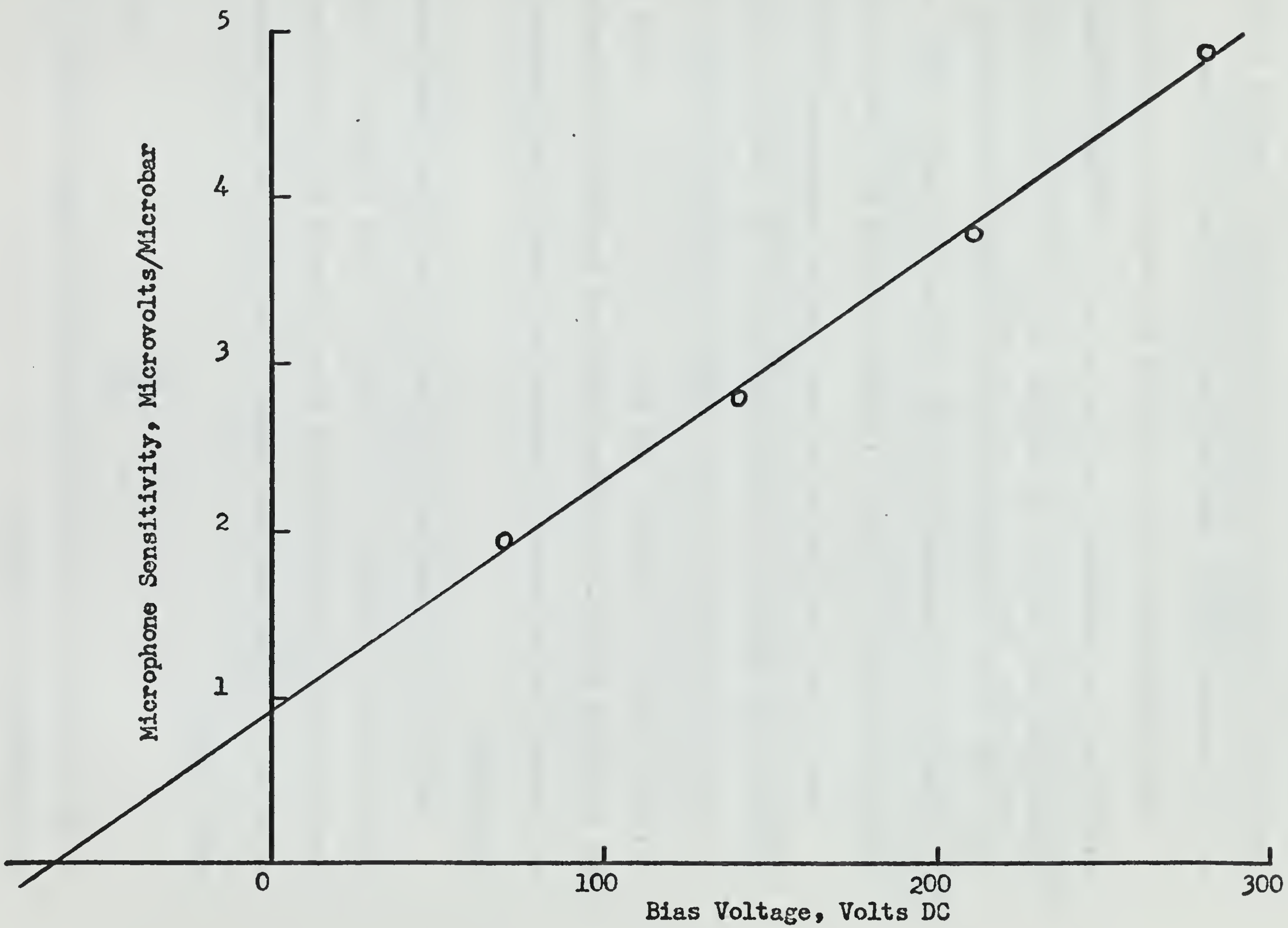
To verify this assumption, microphone sensitivity as a function of applied dc voltage was experimentally determined at 40 kHz and plotted in Fig. 24. The applied bias voltage apparently was not the dc voltage applied to the transducer: there appears to be an opposing potential of 65 volts inherent in the film. With a battery voltage of 280 volts, it would appear that the true bias was 215 volts. If the battery polarity were reversed, one should expect a true bias of 345 volts, an increase of about 60 percent. This polarity was reversed and an increase in sensitivity of 40 percent observed. This was consistent with expectations.

The most probably cause of this reduced bias is that application of the dc voltage to the mylar film causes the molecules to orient themselves with dipole moments opposing the direction of the



Receiving Sensitivities Taken One Month Apart

Figure 23



Sensitivity as a Function of Bias Voltage

Figure 24

applied field and this alignment reduces the voltage across the transducer by the amount of induced polarization. This results in an uncertainty in the sensitivity data which depends on the amount of polarization induced in the dielectric. In Fig. 23 for example, the sensitivities are about 4.1 dB less than would be expected if the total dc voltage applied were realized across the transducer.

This disadvantage can be overcome by permanently polarizing the mylar film. The technique for doing so and a discussion of results obtained has been reported by Sessler and West [12] and by Sessler [13]. For future experimentation with this type of transducer, it would appear that permanently polarizing the film would permit more predictable results and would eliminate the need for biasing circuits.

With x_o being defined as the equilibrium displacement of the film with bias applied, it would seem that if the bias were subject to significant variation, then x_o would be similarly affected. This is probably true in air where the bias is the only force acting on the diaphragm during equilibrium conditions but when the transducer is in water, the hydrostatic pressure acts against the diaphragm at equilibrium.

Table 4 gives experimental values of the blocked capacitance of a one cm radius transducer as a function of bias voltage. The data were taken with the transducer in 30 cm of water and the measured values of C_o differ from each other by less than the experimental error. Since

$$C_o = \frac{\epsilon A}{x_o} \tag{2-7a}$$

it can be said that x_o does not significantly change with bias when the transducer is in water.

BIAS (V)	C_o (pF)
100	338 $\pm$16
200	350 $\pm$13
300	351 $\pm$10

Effect on Blocked Capacitance of Changing
Bias Voltage with the Transducer in Water

Table 4

6. Acknowledgements

The continuing advice and assistance of Professor Alan B. Coppens of the U.S. Naval Postgraduate School is gratefully acknowledged.

Thanks are also due to Mr. Harold Whitfill for his technical support and to Professors O.B. Wilson and J.V. Sanders for their valuable suggestions.

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APPENDIX I

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C      THIS PROGRAM WILL PROVIDE THE USER WITH THE MAGNITUDE AND PHASE
C      OF THE SOURCE LEVEL OF A SOLID DIELECTRIC ELECTROACOUSTIC TRANSDU
C      CER AS A FUNCTION OF FREQUENCY WHEN THE SIGNAL VOLTAGE INPUT IS
C      OF UNIT MAGNITUDE. THIS PARTICULAR PROGRAM IS APPLICABLE WHEN THE
C      TRANSDUCER MAY BE CONSIDERED A SIMPLE SOURCE IN THE FREQUENCY
C      RANGE OF INTEREST.
C      INPUTS---SEQUENCE OF DATA CARDS FOLLOWS (ALL DATA IN MKSE UNITS)
C        FORMAT      DESCRIPTION
C        F3.0,6E10.4 BIAS VOLTAGE,BLOCKED CAPACITANCE,DISPLACEMENT WITH
C                    APPLIED BIAS,PISTON RADIUS,MINIMUM FREQUENCY OF INTE
C                    REST EXPRESSED IN INTEGRAL MULTIPLES OF TEN,MAXIMUM
C                    FREQUENCY IN INTEGRAL UNITS OF TEN (MAX FREQ CANNOT
C                    EXCEED MIN FREQ BY MORE THAN 12 ORDERS OF MAGNITUDE)
C                    DENSITY OF THE MEDIUM
C        6E10.4      MASS OF THE FOIL,MECHANICAL RESISTANCE OF THE TRANSD
C                    UCER,STIFFNESS OF THE TRANDDUCER,INPUT RESISTANCE(EL
C                    ECTRICAL),VELOCITY OF SOUND IN THE MEDIUM,STRAY INPU
C                    T CAPACITANCE.
       COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
       READ 2,BIAS,CAPA,DISPL,RADIUS,FMIN,FMAX,RHO
     2 FORMAT(F3.0,6E10.4)
       TURNS=BIAS*CAPA/DISPL
       READ 5,FMASS,FRES,FSTIFN,RESIST,VEL
    5  FORMAT(5E10.4)
       PRINT 27
    27 FORMAT( 83H1THE PARAMETERS THAT DESCRIBE THE TRANSDUCER EQUIVALENT
      1CIRCUIT ARE (ALL UNITS MKSA),////)
       PRINT 31,BIAS
    31 FORMAT(14H BIAS VOLTAGE= F4.0,//)
       PRINT 33,CAPA
    33 FORMAT(21H BLOCKED CAPACITANCE= 1PE10.4,//)
       PRINT 35,DISPL
```

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```
   35 FORMAT(22H INITIAL DISPLACEMENT= 1PE10.4,//)
      PRINT 37, RADIUS
   37 FORMAT(19H TRANSDUCER RADIUS= 1PE10.4,//)
      PRINT 41, FMASS
   41 FORMAT(15H MASS OF MYLAR= 1PE10.4,//)
      PRINT 43,FRES
   43 FORMAT(23H MECHANICAL RESISTANCE= 1PE10.4,//)
      PRINT 45, FSTIFN
   45 FORMAT(22H MECHANICAL STIFFNESS= 1PE10.4,//)
      PRINT 47,RESIST
   47 FORMAT(18H INPUT RESISTANCE= 1PE10.4,////)
      PRINT 100
 100  FORMAT(5X,10H FREQUENCY,10X,13H MAGNITUDE(DB,10X,11H PHASE(DEG))
      PRINT 101
  101 FORMAT(25X,20H RE 1 MICROBAR/VOLT))
      TOTALC=CAPA+STRAY
      DIMENSION FREQ(12,10),DBMAG(12,10),PHASE(12,10),C(10)
      C(1)=0.0
      C(2)=.301029996
      C(3)=.477121255
      C(4)=.602059991
      C(5)=.698970004
      C(6)=.77815125
      C(7)=.84509804
      C(8)=.903089987
      C(9)=.954242509
      KSTART=LOG10F(FMIN)
      KEND=LOG10F(FMAX)
      DO 96 I=KSTART,KEND
      AI=I
      DO 95 N=1,9
      FREQ(I,N)=10.**(AI+C(N))
      OMEGA=FREQ(I,N)*6.2832
      ARG=2.*OMEGA*RADIUS/VEL
      AMASS=((2.*OMEGA*RADIUS/VEL)*(1./(4.+((OMEGA*RADIUS/VEL)**2))))/4.
      A1=0.0
```

```
203 A2=(OMEGA**2)*CAPA*(RADIUS**2)*RHO*TURNS/2.
200 RONE=((OMEGA**2)*(RADIUS**2)/((4.*(VEL**2))+(OMEGA**2)*(RADIUS**2)
   1))/4.
    CALL REACT
    A3=(OMEGA**2)*RESIST*(CAPA**2)*((RHO*VEL*3.1416*(RADIUS**2)*RONE
   1)+FRES)+OMEGA*CAPA*((RHO*VEL*3.1416*(RADIUS**2)*AMASS)+XMECH)+(TUR
   2NS**2)
    A4=(OMEGA**2)*RESIST*(CAPA**2)*((RHO*VEL*3.1416*(RADIUS**2)*AMASS)
   1+XMECH)+CAPA*((RHO*VEL*3.1416*(RADIUS**2)*RONE)+FRES)
    CALL DIVD(A1,A2,A3,A4,A5,A6,K1)
    AMOD=SQRTF((A5*A5)+(A6*A6))
    DBMAG(I,N)=20.*(LOG10F(AMOD)+1.)
    RATIO=A6/A5
    PHASE(I,N)=(ATANF(RATIO))*57.3
    PRINT 105, FREQ(I,N),DBMAG(I,N),PHASE(I,N)
95  CONTINUE
96  CONTINUE
105 FORMAT(5X,F12.0,15X,F5.1,15X,F4.0,/)
    END
    SUBROUTINE REACT
    COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
    XMECH=(OMEGA*FMASS)-(FSTIFN/OMEGA)
    RETURN
    END
    SUBROUTINE SERIES
    DIMENSION T(2500)
    COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
    NO=1
    X=ARG
    KODE=0
    CALL BES(NO,X,KODE,RESULT,T)
    RONE=1.-2.*RESULT/ARG
    RETURN
    END
    SUBROUTINE BES(NO,X,KODE,RESULT,T)                                    00000000
    DIMENSION T(2500)
```

```
107   FORMAT(55H1NEGATIVE ORDER NOT ACCEPTED IN BESSEL FUNCTION ROUTINE)
      KLAM=1
      KO=NO+1
      IF(X) 6,1,6
1     IF(NO) 4,2,3
2     T(KO)=1.0
      RESULT=1.0
      RETURN
4     IF(KO) 5,10,3
3     RESULT=0
      RETURN
10    RESULT=9.999999999E200
      RETURN
5      PRINT 107
      STOP1
6     IF(NO) 5,7,7
7     IF(KODE) 8,9,8
8     KLAM=KLAM+1
9     JO=2*XFIXF(X)
      MO=NO
      IF(MO-JO) 11,12,12
11    MO=JO
12    MO=MO+11
      T(MO)=0.
      LUB=MO-1
      T(LUB)=1.0E-300
      GO TO (23,51),KLAM
23    F=2*LUB
      MO=MO-3
      I2=MO
24    F=F-2.
      T(I2+1)=F/X*T(I2+2)-T(I2+3)
      IF(I2)26,26,25
25    I2=I2-1
      GO TO 24
26    SUM=T(1)
```

```
      DO40 J=3,MO,2
40    SUM=SUM+2.*T(J)
      F=1./SUM
      DO 50 J= 1,KO
50    T(J)=T(J)*F
      RESULT=T(KO)
      RETURN
51    F=2*LUB-2
      MO=MO-3
      I2=MO
511   T(I2+1)=F/X*T(I2+2)+T(I2+3)
      IF(I2)53,53,52
52    I2=I2-1
      F=F-2.
      GO TO 511
53    SUM=T(1)
      DO 70 J=2,MO
70    SUM=SUM+2.*T(J)
      F=1./(SUM*EXPF(X))
      DO 80 J=1,KO
80    T(J)=T(J)*F
      RESULT=T(KO)
      RETURN
      END
      SUBROUTINE XONE
      DIMENSION TERM(10)
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      IF(ARG-1.)4,5,5
    4 AMASS=(ARG/3.)-((ARG**3)/45.)+(ARG**5)/1575.
      RETURN
    5 IF(ARG-50.)6,15,15
    6 FIRST=ARG/3.
      TERM(1)=FIRST
      AMASS=TERM(1)
      N=2
  100 AI=N
```

```
      I=N
      TERM(2)=(TERM(1))*((ARG**2)/((1.+2.*AI)*(2.*AI-1.)))*(-1.**(2*I-1)
     1)
      IF(ABSF(TERM(2))-.00001)12,10,10
   10 N=N+1
   11 AMASS=AMASS+TERM(2)
      TERM(1)=TERM(2)
      GO TO 100
   12 RETURN
   15 AMASS=1./ARG
      RETURN
      END
       SUBROUTINE    DIVD(XR,XI,YR,YI,ZR,ZI,KER)
       CALL PROD(XR,XI,YR,-YI,B1,B2,PR,PI,DR,DI)
          LDA(B2)    AJP1(1)    ENA(3)     SLJ(3)
 2        ENA(2)     SLJ(3)
 1     T=DR*DR+DI*DI
          LDA(B1)   -FDV(B2)   +EXF7(141B)SLJ(2)     STA(B1)
          LDA(PR)    FDV(T)    -FMU(B1)  +EXF7(141B)SLJ(2)     STA(ZR)
          LDA(PI)    FDV(T)    -FMU(B1)  +EXF7(141B)SLJ(2)    STA(ZI)ENA(1)
 3        STA(KER)
       END
       SUBROUTINE    MULT(XR,XI,YR,YI,ZR,ZI,KER)
       CALL PROD(XR,XI,YR,YI,B1,B2,PR,PI,D1,D2)
          LDA(B2)   -FMU(B1)   +EXF7(141B)SLJ(1)     STA(B1)
          LDA(PR)   -FMU(B1)   +EXF7(141B)SLJ(1)     STA(ZR)
          LDA(PI)   -FMU(B1)   +EXF7(141B)SLJ(1)     STA(ZI)
          ENA(1)     STA(KER)   SLJ(L+2)
 1        ENA(2)     STA(KER)
       END
       SUBROUTINE    PROD(XR,XI,YR,YI,B1,B2,PR,PI,DR,DI)
       CALL NORM(XR,XI,B1,AR,AI)
       CALL NORM(YR,YI,B2,DR,DI)
       PR=AR*DR-AI*DI
       PI=AI*DR+AR*DI
       END
```

```
      SUBROUTINE    NORM(A1,A2,B1,S1,S2)                                00000240
1A       SLJ(1)    +SEV7(70000B)          ZRO(0)    +ZRO(4000B)ZRO(0)  .00000250
 1       LDA(1A+1) LDQ(A1)    QJP2(L+1) LQC(A1)    STL(E)     LDQ(A2)   00000260
         QJP2(L+1) LQC(A2)    LDL(1A+1)+THS(E)     SLJ(L+2)   LDA(E)    00000270
        +AJP1(L+2) STA(S1)    STA(B1)   SLJ(L+5)  +ADD(1A+2)  STA(B1)   00000280
         LDA(A1)   FDV(B1)    STA(S1)   LDA(A2)    FDV(B1)   +STA(S2)  .00000290
```

```
C     THIS PROGRAM WILL PROVIDE THE USER WITH THE MAGNITUDE AND PHASE
C     OF THE SOURCE LEVEL OF A SOLID DIELECTRIC ELECTROACOUSTIC TRANSDU
C     CER AS A FUNCTION OF FREQUENCY WHEN THE SIGNAL VOLTAGE INPUT IS
C     OF UNIT MAGNITUDE. THIS PARTICULAR PROGRAM IS APPLICABLE WHEN THE
C     TRANSDUCER CAN BE REGARDED AS A PLANE PISTON IN AN INFINITE BAFFLE
C     IN THF FREQUENCY RANGE OF INTEREST.
C     INPUTS---SEQUENCE OF DATA CARDS FOLLOWS (ALL DATA IN MKSE UNITS)
C       FORMAT      DESCRIPTION
C       F3.0,6E10.4 BIAS VOLTAGE,BLOCKED CAPACITANCE,DISPLACEMENT WITH
C                   APPLIED BIAS,PISTON RADIUS,MINIMUM FREQUENCY OF INTE
C                   REST EXPRESSED IN INTEGRAL MULTIPLES OF TEN,MAXIMUM
C                   FREQUENCY IN INTEGRAL UNITS OF TEN (MAX FREQ CANNOT
C                   EXCEED MIN FREQ BY MORE THAN 12 ORDERS OF MAGNITUDE)
C                   DENSITY OF THE MEDIUM
C       6E10.4      MASS OF THE FOIL,MECHANICAL RESISTANCE OF THE TRANSD
C                   UCER,STIFFNESS OF THE TRANDDUCER,INPUT RESISTANCE(EL
C                   ECTRICAL),VELOCITY OF SOUND IN THE MEDIUM,STRAY INPU
C                   T CAPACITANCE.
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      READ 2,BIAS,CAPA,DISPL,RADIUS,FMIN,FMAX,RHO
    2 FORMAT(F3.0,6E10.4)
      TURNS=BIAS*CAPA/DISPL
      READ 5,FMASS,FRES,FSTIFN,RESIST,VEL
    5 FORMAT(5E10.4)
      PRINT 27
   27 FORMAT( 83H1THE PARAMETERS THAT DESCRIBE THE TRANSDUCER EQUIVALENT
     1CIRCUIT ARE (ALL UNITS MKSA),////)
      PRINT 31,BIAS
   31 FORMAT(14H BIAS VOLTAGE= F4.0,//)
      PRINT 33,CAPA
   33 FORMAT(21H BLOCKED CAPACITANCE= 1PE10.4,//)
      PRINT 35,DISPL
   35 FORMAT(22H INITIAL DISPLACEMENT= 1PE10.4,//)
      PRINT 37, RADIUS
   37 FORMAT(19H TRANSDUCER RADIUS= 1PE10.4,//)
      PRINT 41, FMASS
```

```
  41 FORMAT(15H MASS OF MYLAR= 1PE10.4,//)
     PRINT 43,FRES
  43 FORMAT(23H MECHANICAL RESISTANCE= 1PE10.4,//)
     PRINT 45, FSTIFN
  45 FORMAT(22H MECHANICAL STIFFNESS= 1PE10.4,//)
     PRINT 47,RESIST
  47 FORMAT(18H INPUT RESISTANCE= 1PE10.4,////)
     PRINT 100
100  FORMAT(5X,10H FREQUENCY,10X,13H MAGNITUDE(DB,10X,11H PHASE(DEG))
     PRINT 101
 101 FORMAT(25X,20H RE 1 MICROBAR/VOLT))
     TOTALC=CAPA+STRAY
     DIMENSION FREQ(12,10),DBMAG(12,10),PHASE(12,10),C(10)
     C(1)=0.0
     C(2)=.301029996
     C(3)=.477121255
     C(4)=.602059991
     C(5)=.698970004
     C(6)=.77815125
     C(7)=.84509804
     C(8)=.903089987
     C(9)=.954242509
     KSTART=LOG10F(FMIN)
     KEND=LOG10F(FMAX)
     DO 96 I=KSTART,KEND
     AI=I
     DO 95 N=1,9
     FREQ(I,N)=10.**(AI+C(N))
     OMEGA=FREQ(I,N)*6.2832
     ARG=2.*OMEGA*RADIUS/VEL
     CALL XONE
     AMASS=4.*AMASS/3.1416
     A1=0.0
     IF(ARG-1000.) 204,204,200
200  RONE=1.
     GO TO 203
```

```
204   CALL SERIES
 203  A2=(OMEGA**2)*CAPA*(RADIUS**2)*RHO*TURNS/2.
      CALL REACT
      A3=(OMEGA**2)*RESIST*(CAPA**2)*((RHO*VEL*3.1416*(RADIUS**2)*RONE
     1)+FRES)+OMEGA*CAPA*((RHO*VEL*3.1416*(RADIUS**2)*AMASS)+XMECH)+(TUR
     2NS**2)
      A4=(OMEGA**2)*RESIST*(CAPA**2)*((RHO*VEL*3.1416*(RADIUS**2)*AMASS)
     1+XMECH)+CAPA*((RHO*VEL*3.1416*(RADIUS**2)*RONE)+FRES)
      CALL DIVD(A1,A2,A3,A4,A5,A6,K1)
      AMOD=SQRTF((A5*A5)+(A6*A6))
      DBMAG(I,N)=20.*(LOG10F(AMOD)+1.)
      RATIO=A6/A5
      PHASE(I,N)=(ATANF(RATIO))*57.3
      PRINT 105, FREQ(I,N),DBMAG(I,N),PHASE(I,N)
 95   CONTINUE
 96   CONTINUE
 105  FORMAT(5X,F12.0,15X,F5.1,15X,F4.0,/)
      END
      SUBROUTINE REACT
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      XMECH=(OMEGA*FMASS)-(FSTIFN/OMEGA)
      RETURN
      END
      SUBROUTINE SERIES
      DIMENSION T(2500)
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      NO=1
      X=ARG
      KODE=0
      CALL BES(NO,X,KODE,RESULT,T)
      RONE=1.-2.*RESULT/ARG
      RETURN
      END
      SUBROUTINE BES(NO,X,KODE,RESULT,T)                                00000000
      DIMENSION T(2500)
107   FORMAT(55H1NEGATIVE ORDER NOT ACCEPTED IN BESSEL FUNCTION ROUTINE)00000020
```

```
      KLAM=1
      KO=NO+1
      IF(X) 6,1,6
1     IF(NO) 4,2,3
2     T(KO)=1.0
      RESULT=1.0
      RETURN
4     IF(KO) 5,10,3
3     RESULT=0
      RETURN
10    RESULT=9.999999999E200
      RETURN
 5     PRINT 107
      STOP1
6     IF(NO) 5,7,7
7     IF(KODE) 8,9,8
8     KLAM=KLAM+1
9     JO=2*XFIXF(X)
      MO=NO
      IF(MO-JO) 11,12,12
11    MO=JO
12    MO=MO+11
      T(MO)=0.
      LUB=MO-1
      T(LUB)=1.0E-300
      GO TO (23,51),KLAM
23    F=2*LUB
      MO=MO-3
      I2=MO
24    F=F-2.
      T(I2+1)=F/X*T(I2+2)-T(I2+3)
      IF(I2)26,26,25
25    I2=I2-1
      GO TO 24
26    SUM=T(1)
      DO40 J=3,MO,2
```

```
40    SUM=SUM+2.*T(J)
      F=1./SUM
      DO 50 J= 1,KO
50    T(J)=T(J)*F
      RESULT=T(KO)
      RETURN
51    F=2*LUB-2
      MO=MO-3
      I2=MO
511   T(I2+1)=F/X*T(I2+2)+T(I2+3)
      IF(I2)53,53,52
52    I2=I2-1
      F=F-2.
      GO TO 511
53    SUM=T(1)
      DO 70 J=2,MO
70    SUM=SUM+2.*T(J)
      F=1./(SUM*EXPF(X))
      DO 80 J=1,KO
80    T(J)=T(J)*F
      RESULT=T(KO)
      RETURN
      END
      SUBROUTINE XONE
      DIMENSION TERM(10)
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      IF(ARG-1.)4,5,5
    4 AMASS=(ARG/3.)-((ARG**3)/45.)+(ARG**5)/1575.
      RETURN
    5 IF(ARG-50.)6,15,15
    6 FIRST=ARG/3.
      TERM(1)=FIRST
      AMASS=TERM(1)
      N=2
  100 AI=N
      I=N
```

```
      TERM(2)=(TERM(1))*((ARG**2)/((1.+2.*AI)*(2.*AI-1.)))*(-1.**(2*I-1)
     1)
      IF(ABSF(TERM(2))-.00001)12,10,10
   10 N=N+1
   11 AMASS=AMASS+TERM(2)
      TERM(1)=TERM(2)
      GO TO 100
   12 RETURN
   15 AMASS=1./ARG
      RETURN
      END
       SUBROUTINE   DIVD(XR,XI,YR,YI,ZR,ZI,KER)
       CALL PROD(XR,XI,YR,-YI,B1,B2,PR,PI,DR,DI)
          LDA(B2)   AJP1(1)   ENA(3)    SLJ(3)
  2       ENA(2)    SLJ(3)
  1    T=DR*DR+DI*DI
          LDA(B1)  -FDV(B2)  +EXF7(141B)SLJ(2)    STA(B1)
          LDA(PR)   FDV(T)   -FMU(B1)  +EXF7(141B)SLJ(2)    STA(ZR)
          LDA(PI)   FDV(T)   -FMU(B1)  +EXF7(141B)SLJ(2)   STA(ZI)ENA(1)
  3       STA(KER)
       END
       SUBROUTINE   MULT(XR,XI,YR,YI,ZR,ZI,KER)
       CALL PROD(XR,XI,YR,YI,B1,B2,PR,PI,D1,D2)
          LDA(B2)  -FMU(B1)  +EXF7(141B)SLJ(1)    STA(B1)
          LDA(PR)  -FMU(B1)  +EXF7(141B)SLJ(1)    STA(ZR)
          LDA(PI)  -FMU(B1)  +EXF7(141B)SLJ(1)    STA(ZI)
          ENA(1)    STA(KER)  SLJ(L+2)
  1       ENA(2)    STA(KER)
       END
       SUBROUTINE   PROD(XR,XI,YR,YI,B1,B2,PR,PI,DR,DI)
       CALL NORM(XR,XI,B1,AR,AI)
       CALL NORM(YR,YI,B2,DR,DI)
       PR=AR*DR-AI*DI
       PI=AI*DR+AR*DI
       END
       SUBROUTINE   NORM(A1,A2,B1,S1,S2)
```

```
1A      SLJ(1)    +SEV7(70000B)        ZRO(0)    +ZRO(4000B)ZRO(0)      .00000250
 1      LDA(1A+1) LDQ(A1)    QJP2(L+1) LQC(A1)    STL(E)     LDQ(A2)      00000260
        QJP2(L+1) LQC(A2)    LDL(1A+1)+THS(E)     SLJ(L+2)   LDA(E)       00000270
       +AJP1(L+2) STA(S1)    STA(B1)   SLJ(L+5) +ADD(1A+2) STA(B1)        00000280
        LDA(A1)   FDV(B1)    STA(S1)   LDA(A2)    FDV(B1)   +STA(S2)     .00000290
      END                                                                 000* 300
```

```
C     THIS PROGRAM WILL PROVIDE THE USER WITH THE MICROPHONE SENSITIVITY
C     OF A MYLAR TRANSDUCER IN DB RELATIVE TO ONE VOLT PER MICROBAR AS A
C     FUNCTION OF FREQUENCY. THIS PARTICULAR PROGRAM IS APPLICABLE
C     WHEN THE WAVELENGTH IS LARGER THAN THE DIAMETER OF THE DIAPHRAGM.
C     INPUTS---SEQUENCE OF DATA CARDS FOLLOWS (ALL DATA IN MKSE UNITS)
C       FORMAT      DESCRIPTION
C       F3.0,6E10.4 BIAS VOLTAGE,BLOCKED CAPACITANCE,DISPLACEMENT WITH
C                   APPLIED BIAS,PISTON RADIUS,MINIMUM FREQUENCY OF INTE
C                   REST EXPRESSED IN INTEGRAL MULTIPLES OF TEN,MAXIMUM
C                   FREQUENCY IN INTEGRAL UNITS OF TEN (MAX FREQ CANNOT
C                   EXCEED MIN FREQ BY MORE THAN 12 ORDERS OF MAGNITUDE)
C                   DENSITY OF THE MEDIUM
C       5E10.4      MASS OF THE FOIL,MECHANICAL RESISTANCE OF THE TRANSD
C                   UCER,STIFFNESS OF THE TRANDDUCER,INPUT RESISTANCE(EL
C                   ECTRICAL),VELOCITY OF SOUND IN THE MEDIUM
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      READ 2,BIAS,CAPA,DISPL,RADIUS,FMIN,FMAX,RHO
    2 FORMAT(F3.0,6E10.4)
      TURNS=BIAS*CAPA/DISPL
      READ 5,FMASS,FRES,FSTIFN,VEL
5     FORMAT(4E10.4)
      PRINT 27
27    FORMAT( 83H1THE PARAMETERS THAT DESCRIBE THE TRANSDUCER EQUIVALENT
     1CIRCUIT ARE (ALL UNITS MKSA),////)
      PRINT 31,BIAS
31    FORMAT(14H BIAS VOLTAGE= F4.0,//)
      PRINT 33,CAPA
33    FORMAT(21H BLOCKED CAPACITANCE= 1PE10.4,//)
      PRINT 35,DISPL
35    FORMAT(22H INITIAL DISPLACEMENT= 1PE10.4,//)
      PRINT 37, RADIUS
37    FORMAT(19H TRANSDUCER RADIUS= 1PE10.4,//)
      PRINT 41, FMASS
41    FORMAT(15H MASS OF MYLAR= 1PE10.4,//)
      PRINT 43,FRES
43    FORMAT(23H MECHANICAL RESISTANCE= 1PE10.4,//)
```

```
      PRINT 45, FSTIFN
   45 FORMAT(22H MECHANICAL STIFFNESS= 1PE10.4,//)
      PRINT 100
  100 FORMAT(5X,10H FREQUENCY,10X,13H MAGNITUDE(DB,10X,11H PHASE(DEG))
      PRINT 101
  101 FORMAT(25X,20H RE 1 MICROBAR/VOLT))
      DIMENSION FREQ(12,10),DBMAG(12,10),PHASE(12,10),C(10)
      C(1)=0.0
      C(2)=.301029996
      C(3)=.477121255
      C(4)=.602059991
      C(5)=.698970004
      C(6)=.77815125
      C(7)=.84509804
      C(8)=.903089987
      C(9)=.954242509
      KSTART=LOG10F(FMIN)
      KEND=LOG10F(FMAX)
      DO 96 I=KSTART,KEND
      AI=I
      DO 95 N=1,9
      FREQ(I,N)=10.**(AI+C(N))
      OMEGA=FREQ(I,N)*6.2832
      ARG=2.*OMEGA*RADIUS/VEL
      CALL XONE
      AMASS=((2.*OMEGA*RADIUS/VEL)*(1./(4.+((OMEGA*RADIUS/VEL)**2))))/4.
      A1=3.1416*(RADIUS**2)*TURNS
  200 RONE=((OMEGA**2)*(RADIUS**2)/((4.*(VEL**2))+(OMEGA**2)*(RADIUS**2)
     1))/4.
  203 A2=0.0
      CALL REACT
      A3=-(XMECH+(RHO*VEL*3.1416*(RADIUS**2)*AMASS))*OMEGA*CAPA
      A4=OMEGA*CAPA*(FRES+(RHO*VEL*3.1416*(RADIUS**2)*RONE))
      CALL DIVD(A1,A2,A3,A4,A5,A6,K1)
      AMOD=SQRTF((A5*A5)+(A6*A6))
      DBMAG(I,N)=20.*(LOG10F(AMOD)-1.)
```

```
      RATIO=A6/A5
      PHASE(I,N)=(ATANF(RATIO))*57.3
      PRINT 105, FREQ(I,N),DBMAG(I,N),PHASE(I,N)
 95   CONTINUE
 96   CONTINUE
 105  FORMAT(5X,F12.0,15X,F6.1,15X,F4.0,/)
      END
      SUBROUTINE REACT
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      XMECH=(OMEGA*FMASS)-(FSTIFN/OMEGA)
      END
      SUBROUTINE SERIES
      DIMENSION T(2500)
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      NO=1
      X=ARG
      KODE=0
      CALL BES(NO,X,KODE,RESULT,T)
      RONE=1.-2.*RESULT/ARG
      RETURN
      END
      SUBROUTINE BES(NO,X,KODE,RESULT,T)
      DIMENSION T(2500)
107   FORMAT(55H1NEGATIVE ORDER NOT ACCEPTED IN BESSEL FUNCTION ROUTINE)
      KLAM=1
      KO=NO+1
      IF(X) 6,1,6
1     IF(NO) 4,2,3
2     T(KO)=1.0
      RESULT=1.0
      RETURN
4     IF(KO) 5,10,3
3     RESULT=0
      RETURN
10    RESULT=9.999999999E200
      RETURN
```

```
5     PRINT 107
      STOP1
6     IF(NO) 5,7,7
7     IF(KODE) 8,9,8
8     KLAM=KLAM+1
9     JO=2*XFIXF(X)
      MO=NO
      IF(MO-JO) 11,12,12
11    MO=JO
12    MO=MO+11
      T(MO)=0.
      LUB=MO-1
      T(LUB)=1.0E-300
      GO TO (23,51),KLAM
23    F=2*LUB
      MO=MO-3
      I2=MO
24    F=F-2.
      T(I2+1)=F/X*T(I2+2)-T(I2+3)
      IF(I2)26,26,25
25    I2=I2-1
      GO TO 24
26    SUM=T(1)
      DO40 J=3,MO,2
40    SUM=SUM+2.*T(J)
      F=1./SUM
      DO 50 J= 1,KO
50    T(J)=T(J)*F
      RFSULT=T(KO)
      RETURN
51    F=2*LUB-2
      MO=MO-3
      I2=MO
511   T(I2+1)=F/X*T(I2+2)+T(I2+3)
      IF(I2)53,53,52
52    I2=I2-1
```

```
      F=F-2.
      GO TO 511
53    SUM=T(1)
      DO 70 J=2,MO
70    SUM=SUM+2.*T(J)
      F=1./(SUM*EXPF(X))
      DO 80 J=1,KO
80    T(J)=T(J)*F
      RESULT=T(KO)
      RETURN
      END
      SUBROUTINE XONE
      DIMENSION TERM(10)
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      IF(ARG-1.)4,5,5
    4 AMASS=(ARG/3.)-((ARG**3)/45.)+(ARG**5)/1575.
      RETURN
    5 IF(ARG-50.)6,15,15
    6 FIRST=ARG/3.
      TERM(1)=FIRST
      AMASS=TERM(1)
      N=2
  100 AI=N
      I=N
      TERM(2)=(TERM(1))*((ARG**2)/((1.+2.*AI)*(2.*AI-1.)))*(-1.**(2*I-1)
     1)
      IF(ABSF(TERM(2))-.00001)12,10,10
   10 N=N+1
   11 AMASS=AMASS+TERM(2)
      TERM(1)=TERM(2)
      GO TO 100
   12 RETURN
   15 AMASS=1./ARG
      RETURN
      END
       SUBROUTINE   DIVD(XR,XI,YR,YI,ZR,ZI,KER)
```

```
      CALL PROD(XR,XI,YR,-YI,B1,B2,PR,PI,DR,DI)                          00000010
         LDA(B2)   AJP1(1)   ENA(3)    SLJ(3)                           .00000020
 2       ENA(2)    SLJ(3)                                               .00000030
 1    T=DR*DR+DI*DI                                                      00000040
         LDA(B1)  -FDV(B2)  +EXF7(141B)SLJ(2)    STA(B1)                 00000050
         LDA(PR)   FDV(T)   -FMU(B1)  +EXF7(141B)SLJ(2)    STA(ZR)       00000060
         LDA(PI)   FDV(T)   -FMU(B1)  +EXF7(141B)SLJ(2)   STA(ZI)ENA(1)00000070
 3       STA(KER)                                                       .00000080
      END                                                                00*   90
      SUBROUTINE   MULT(XR,XI,YR,YI,ZR,ZI,KER)                           00000100
      CALL PROD(XR,XI,YR,YI,B1,B2,PR,PI,D1,D2)                           00000110
         LDA(B2)  -FMU(B1)  +EXF7(141B)SLJ(1)    STA(B1)                .00000120
         LDA(PR)  -FMU(B1)  +EXF7(141B)SLJ(1)    STA(ZR)                .00000130
         LDA(PI)  -FMU(B1)  +EXF7(141B)SLJ(1)    STA(ZI)                 00000140
         ENA(1)    STA(KER)  SLJ(L+2)                                   .00000150
 1       ENA(2)    STA(KER)                                              00000160
      END                                                                0000 170
      SUBROUTINE   PROD(XR,XI,YR,YI,B1,B2,PR,PI,DR,DI)                   00000180
      CALL NORM(XR,XI,B1,AR,AI)                                          00000190
      CALL NORM(YR,YI,B2,DR,DI)                                          00000200
      PR=AR*DR-AI*DI                                                     00000210
      PI=AI*DR+AR*DI                                                     00000220
      END                                                                0000 230
      SUBROUTINE   NORM(A1,A2,B1,S1,S2)                                  00000240
1A       SLJ(1)   +SEV7(70000B)        ZRO(0)   +ZRO(4000B)ZRO(0)       .00000250
 1       LDA(1A+1) LDQ(A1)   QJP2(L+1) LQC(A1)   STL(E)    LDQ(A2)       00000260
         QJP2(L+1) LQC(A2)   LDL(1A+1)+THS(E)    SLJ(L+2)  LDA(E)        00000270
        +AJP1(L+2) STA(S1)   STA(B1)   SLJ(L+5) +ADD(1A+2) STA(B1)       00000280
         LDA(A1)   FDV(B1)   STA(S1)   LDA(A2)   FDV(B1)  +STA(S2)      .00000290
      END                                                                000* 300
```

```
C     THIS PROGRAM WILL PROVIDE THE USER WITH THE MICROPHONE SENSITIVITY
C     OF A MYLAR DIELECTRIC TRANSDUCER IN DB RE ONE VOLT PER MICROBAR.
C     THIS PARTICULAR PROGRAM IS APPLICABLE WHEN THE MICROPHONE MAY BE
C     CONSIDERED A PLANE PISTON IN AN INFINITE BAFFLE. THAT IS TO SAY,
C     WHEN THE WAVELENGTH IS MUCH SMALLER THAN THE DIAMETER OF THE
C     DIAPHRAGM
C     INPUTS---SEQUENCE OF DATA CARDS FOLLOWS (ALL DATA IN MKSE UNITS)
C       FORMAT      DESCRIPTION
C       F3.0,6E10.4 BIAS VOLTAGE,BLOCKED CAPACITANCE,DISPLACEMENT WITH
C                   APPLIED BIAS,PISTON RADIUS,MINIMUM FREQUENCY OF INTE
C                   REST EXPRESSED IN INTEGRAL MULTIPLES OF TEN,MAXIMUM
C                   FREQUENCY IN INTEGRAL UNITS OF TEN (MAX FREQ CANNOT
C                   EXCEED MIN FREQ BY MORE THAN 12 ORDERS OF MAGNITUDE)
C                   DENSITY OF THE MEDIUM
C       5E10.4      MASS OF THE FOIL,MECHANICAL RESISTANCE OF THE TRANSD
C                   UCER,STIFFNESS OF THE TRANDDUCER,INPUT RESISTANCE(EL
C                   ECTRICAL),VELOCITY OF SOUND IN THE MEDIUM
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      READ 2,BIAS,CAPA,DISPL,RADIUS,FMIN,FMAX,RHO
    2 FORMAT(F3.0,6E10.4)
      TURNS=BIAS*CAPA/DISPL
      READ 5,FMASS,FRES,FSTIFN,VFL
    5 FORMAT(4E10.4)
      PRINT 27
   27 FORMAT( 83H1THE PARAMETERS THAT DESCRIBE THE TRANSDUCER EQUIVALENT
     1CIRCUIT ARE (ALL UNITS MKSA),////)
      PRINT 31,BIAS
   31 FORMAT(14H BIAS VOLTAGE= F4.0,//)
      PRINT 33,CAPA
   33 FORMAT(21H BLOCKED CAPACITANCE= 1PE10.4,//)
      PRINT 35,DISPL
   35 FORMAT(22H INITIAL DISPLACEMENT= 1PE10.4,//)
      PRINT 37, RADIUS
   37 FORMAT(19H TRANSDUCER RADIUS= 1PE10.4,//)
      PRINT 41, FMASS
   41 FORMAT(15H MASS OF MYLAR= 1PE10.4,//)
```

```
      PRINT 43,FRES
   43 FORMAT(23H MECHANICAL RESISTANCE= 1PE10.4,//)
      PRINT 45, FSTIFN
   45 FORMAT(22H MECHANICAL STIFFNESS= 1PE10.4,//)
      PRINT 100
  100 FORMAT(5X,10H FREQUENCY,10X,13H MAGNITUDE(DB,10X,11H PHASE(DEG))
      PRINT 101
  101 FORMAT(25X,20H RE 1 MICROBAR/VOLT))
      DIMENSION FREQ(12,10),DBMAG(12,10),PHASE(12,10),C(10)
      C(1)=0.0
      C(2)=.301029996
      C(3)=.477121255
      C(4)=.602059991
      C(5)=.698970004
      C(6)=.77815125
      C(7)=.84509804
      C(8)=.903089987
      C(9)=.954242509
      KSTART=LOG10F(FMIN)
      KEND=LOG10F(FMAX)
      DO 96 I=KSTART,KEND
      AI=I
      DO 95 N=1,9
      FREQ(I,N)=10.**(AI+C(N))
      OMEGA=FREQ(I,N)*6.2832
      ARG=2.*OMEGA*RADIUS/VEL
      CALL XONE
      AMASS=4.*AMASS/3.1416
      A1=3.1416*(RADIUS**2)*TURNS
      IF (ARG-1000.) 204,204,200
  200 RONE=1.
      GO TO 203
  204 CALL SERIES
  203 A2=0.0
      CALL REACT
      A3=-(XMECH+(RHO*VEL*3.1416*(RADIUS**2)*AMASS))*OMEGA*CAPA
```

```
      A4=OMEGA*CAPA*(FRES+(RHO*VEL*3.1416*(RADIUS**2)*RONE))
      CALL DIVD(A1,A2,A3,A4,A5,A6,K1)
      AMOD=SQRTF((A5*A5)+(A6*A6))
      DBMAG(I,N)=20.*(LOG10F(AMOD)-1.)
      RATIO=A6/A5
      PHASE(I,N)=(ATANF(RATIO))*57.3
      PRINT 105, FREQ(I,N),DBMAG(I,N),PHASE(I,N)
 95   CONTINUE
 96   CONTINUE
 105  FORMAT(5X,F12.0,15X,F6.1,15X,F4.0,/)
      END
      SUBROUTINE REACT
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      XMECH=(OMEGA*FMASS)-(FSTIFN/OMEGA)
      END
      SUBROUTINE SERIES
      DIMENSION T(2500)
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      NO=1
      X=ARG
      KODE=0
      CALL BES(NO,X,KODE,RESULT,T)
      RONE=1.-2.*RESULT/ARG
      RETURN
      END
      SUBROUTINE BES(NO,X,KODE,RESULT,T)
      DIMENSION T(2500)
107   FORMAT(55H1NEGATIVE ORDER NOT ACCEPTED IN BESSEL FUNCTION ROUTINE)
      KLAM=1
      KO=NO+1
      IF(X) 6,1,6
1     IF(NO) 4,2,3
2     T(KO)=1.0
      RESULT=1.0
      RETURN
4     IF(KO) 5,10,3
```

```
3     RESULT=0
      RETURN
10    RESULT=9.999999999E200
      RETURN
 5     PRINT 107
      STOP1
6     IF(NO) 5,7,7
7     IF(KODE) 8,9,8
8     KLAM=KLAM+1
9     JO=2*XFIXF(X)
      MO=NO
      IF(MO-JO) 11,12,12
11    MO=JO
12    MO=MO+11
      T(MO)=0.
      LUB=MO-1
      T(LUB)=1.0E-300
      GO TO (23,51),KLAM
23    F=2*LUB
      MO=MO-3
      I2=MO
24    F=F-2.
      T(I2+1)=F/X*T(I2+2)-T(I2+3)
      IF(I2)26,26,25
25    I2=I2-1
      GO TO 24
26    SUM=T(1)
      DO40 J=3,MO,2
40    SUM=SUM+2.*T(J)
      F=1./SUM
      DO 50 J= 1,KO
50    T(J)=T(J)*F
      RESULT=T(KO)
      RETURN
51    F=2*LUB-2
      MO=MO-3
```

```
      I2=MO
511   T(I2+1)=F/X*T(I2+2)+T(I2+3)
      IF(I2)53,53,52
52    I2=I2-1
      F=F-2.
      GO TO 511
53    SUM=T(1)
      DO 70 J=2,MO
70    SUM=SUM+2.*T(J)
      F=1./(SUM*EXPF(X))
      DO 80 J=1,KO
80    T(J)=T(J)*F
      RESULT=T(KO)
      RETURN
      END
      SUBROUTINE XONE
      DIMENSION TERM(10)
      COMMON ARG,AMASS,RONE,FMASS,FSTIFN,OMEGA,XMECH
      IF(ARG-1.)4,5,5
    4 AMASS=(ARG/3.)-((ARG**3)/45.)+(ARG**5)/1575.
      RETURN
    5 IF(ARG-50.)6,15,15
    6 FIRST=ARG/3.
      TERM(1)=FIRST
      AMASS=TERM(1)
      N=2
  100 AI=N
      I=N
      TERM(2)=(TERM(1))*((ARG**2)/((1.+2.*AI)*(2.*AI-1.)))*(-1.**(2*I-1)
     1)
      IF(ABSF(TERM(2))-.00001)12,10,10
   10 N=N+1
   11 AMASS=AMASS+TERM(2)
      TERM(1)=TERM(2)
      GO TO 100
   12 RETURN
```

```
15 AMASS=1./ARG
   RETURN
   END
    SUBROUTINE   DIVD(XR,XI,YR,YI,ZR,ZI,KER)
    CALL PROD(XR,XI,YR,-YI,B1,B2,PR,PI,DR,DI)
       LDA(B2)    AJP1(1)    ENA(3)     SLJ(3)
 2     ENA(2)     SLJ(3)
 1  T=DR*DR+DI*DI
       LDA(B1)  -FDV(B2)   +EXF7(141B)SLJ(2)     STA(B1)
       LDA(PR)    FDV(T)    -FMU(B1)   +EXF7(141B)SLJ(2)     STA(ZR)
       LDA(PI)    FDV(T)    -FMU(B1)   +EXF7(141B)SLJ(2)    STA(ZI)ENA(1)
 3     STA(KER)
    END
    SUBROUTINE   MULT(XR,XI,YR,YI,ZR,ZI,KER)
    CALL PROD(XR,XI,YR,YI,B1,B2,PR,PI,D1,D2)
       LDA(B2)  -FMU(B1)   +EXF7(141B)SLJ(1)     STA(B1)
       LDA(PR)  -FMU(B1)   +EXF7(141B)SLJ(1)     STA(ZR)
       LDA(PI)  -FMU(B1)   +EXF7(141B)SLJ(1)     STA(ZI)
       ENA(1)     STA(KER)   SLJ(L+2)
 1     ENA(2)     STA(KER)
    END
    SUBROUTINE   PROD(XR,XI,YR,YI,B1,B2,PR,PI,DR,DI)
    CALL NORM(XR,XI,B1,AR,AI)
    CALL NORM(YR,YI,B2,DR,DI)
    PR=AR*DR-AI*DI
    PI=AI*DR+AR*DI
    END
    SUBROUTINE   NORM(A1,A2,B1,S1,S2)
1A     SLJ(1)    +SEV7(70000B)          ZRO(0)    +ZRO(4000B)ZRO(0)
 1     LDA(1A+1) LDQ(A1)    QJP2(L+1) LQC(A1)    STL(E)     LDQ(A2)
       QJP2(L+1) LQC(A2)    LDL(1A+1)+THS(E)     SLJ(L+2)   LDA(E)
      +AJP1(L+2) STA(S1)    STA(B1)    SLJ(L+5) +ADD(1A+2) STA(B1)
       LDA(A1)   FDV(B1)    STA(S1)    LDA(A2)    FDV(B1)   +STA(S2)
    END
```

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